Battery Electric Vehicles vs. Internal Combustion Engine Vehicles

A United States-Based Comprehensive Assessment

Arthur D Little

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Executive Summary

A United States-Based Comprehensive Assessment

Battery electric vehicles (BEVs) do not consume gasoline or produce tailpipe carbon emissions, placing the promise of an environmentally sustainable driving experience within reach of the average consumer. However, the question remains: "Do BEVs truly offer an environmental advantage with respect to global warming potential and secondary environmental impacts – and if so, at what cost?"

To address this question, Arthur D. Little conducted a total lifecycle economic cost and environmental impact analysis of Lithium-ion battery electric vehicles (BEVs) versus internal combustion engine vehicles (ICEVs) to further understand BEVs and their transformative potential. This study models the relative impacts of new BEVs and ICEVs in the United States for the latest full calendar year for which data is available, 2015, and it projects the economic and environmental impacts of BEVs and ICEVs over the entire assumed twenty-year lifetime for a US passenger vehicle. Given that this is a rapidly evolving market, our study also forecasts the economic and environmental impacts that new BEVs and ICEVs will have in 2025, taking into account salient expected developments in battery technology, vehicle range, and fuel economy standards.

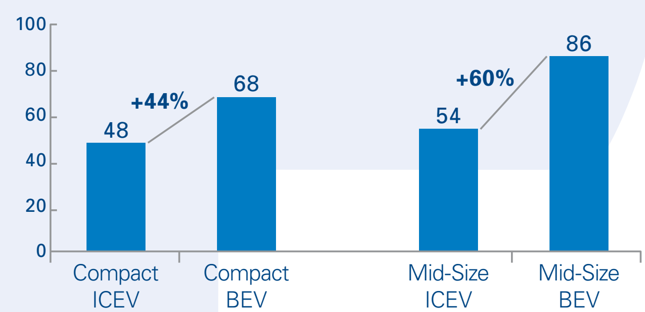
In order to determine the true cost and environmental impacts from BEVs, we performed a comprehensive quantitative analysis excluding any government incentives or subsidies. Our study investigated every stage of the vehicle's lifecycle, from R&D and production, including sourcing of raw materials, through ownership and end-of-life disposal. We evaluated the impacts associated with each component of the vehicle, from the novel technologies and chemistries involved in battery production to the In-Use energy requirements (i.e., gasoline and electricity, from well-to-wheels) necessary to power a vehicle. We constructed models that calculate the 2015 Total Cost of Ownership (TCO), Global Warming Potential (GWP), and Secondary Environmental Impacts (e.g., Human Toxicity Potential characterized as Disability Adjusted Life Years lost) for BEVs and ICEVs. We also forecast how BEV and ICEV technology will evolve over the coming decade and we leveraged this information to model the 2025 TCO, GWP, and Secondary Environmental Impacts for BEVs and ICEVs.

Based on our study, the ultimate environmental and economic reality of electric vehicles is far more complicated than their promise. From an economic perspective, BEVs enjoy some distinct advantages. First, the electricity cost associated with operating a BEV over a distance of one mile is significantly lower than the gasoline cost required to operate a comparable ICEV over the same distance. Second, BEVs cost less to maintain, owing to the relative elegance and simplicity of a battery-electric motor system compared with the frequent maintenance required for operation of an internal combustion system. Third, automotive battery technology has evolved rapidly since the current generation of BEVs came to market, with the price per kilowatt-hour (kWh) of lithium-ion battery packs declining from $1,126 in 2010 to just $300 in 2015 (see Appendix E-1).

These cost advantages, however, are entirely offset by a host of other economic factors. The TCO for a BEV is significantly greater than the TCO for an equivalent ICEV. BEVs in 2015 were, without exception, significantly more expensive to manufacture than comparable ICEVs – due primarily to the cost of battery manufacturing – and they imposed a much higher cost burden on vehicle owners (see Figure 1). Ultimately, this cost burden presents

Figure 1. Total Cost of Ownership over a 20-Year Lifetime for a 2015 ICEV versus an Equivalent BEV

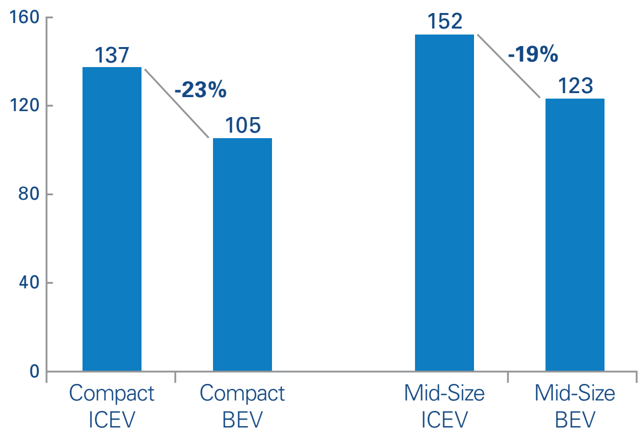
In Thousands of Dollars at Present Value



Source: ADL Analysis

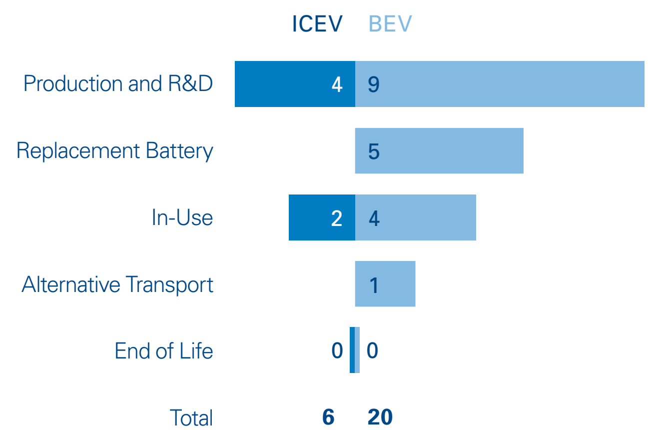
Figure 2. Greenhouse Gas Emissions over a 20-Year Lifetime for a 2015 ICEV versus an Equivalent BEV

In Thousands of Pounds of CO_2e Emissions



Source: ADL Analysis

Figure 3. Days of Life Impact (Death or Disability) for a 2015 Compact Passenger ICEV versus an Equivalent BEV over 20 Years of Ownership



Values do not sum to total due to rounding. Source: ADL Analysis

a significant barrier for wider adoption of BEVs and could explain why their market penetration has been limited to date.

From an environmental perspective, the picture is even more complex. BEVs in 2015 achieve the goal of reducing greenhouse gas emissions relative to comparable ICEVs when considered over a vehicle's lifetime, but this masks an increased human health impact relative to ICEVs and a host of other collateral impacts to the environment (see Figures 2 and 3). While most of the environmental impacts generated by ICEVs are localized to the combustion of gasoline in the vehicle engine, the manufacturing process for BEVs generates a much more widely-dispersed and damaging set of environmental impacts, offsetting a significant portion of their overall advantage with respect to greenhouse gas emissions.

In particular, the usage of heavy metals in the manufacture of lithium-ion battery packs for BEVs combined with pollution generated by the US power grid (e.g. tailings from coal power plants) for the In-Use portion of a BEVs lifecycle generate approximately three times the amount of human toxicity compared to ICEVs (see Figure 3). Given the divergence in where environmental impacts are allocated, it is safe to say that a consumer who chooses to drive a BEV over an ICEV shifts the environmental

Figure 4. Comparison of ADL's Study with Union of Concerned Scientists' and National Bureau of Economic Research's Findings

Impact Area	ADL	UCS	NBER
Total Cost of Ownership	BEV is 44% more expensive than ICEV	Not covered	Not covered
Global Warming Potential	BEV has 23% less GWP impact than ICEV	BEV has 51% less GWP impact than ICEV	BEV has 40% less GWP impact than ICEV
Secondary Environmental Impacts	BEV has 3 times greater Human Toxicity Potential	Not covered	BEV has 3 times greater damages from local pollutants

Source: ADL Analysis, UCS, and NBER

impact of car ownership. As detailed in a recent series of investigative reports by the Washington Post, much of the cobalt and graphite entering the supply chain for lithium-ion batteries is sourced from poorly regulated and heavily polluting mines in Congo[1] and China.[2] While the BEV driver reduces their local contribution to greenhouse gas emissions, they create a more diffuse set of environmental impacts spread across the globe, the consequences of which are largely borne by rural and often disadvantaged communities near the mines from which BEV suppliers source raw materials for battery pack manufacturing.

As part of our study, Arthur D. Little also presents the findings of two other widely-cited reports on the environmental impact of BEVs versus ICEVs – "Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Global Warming Emissions,"[3] from the Union of Concerned Scientists (UCS), and "Environmental Benefits from Driving Electric Vehicles?"[4] from the National Bureau of Economic Research (NBER). Both of these reports examine the environmental impact of BEVs and ICEVs, and both reports describe the policy implications that arise from their findings. However, UCS and NBER reach drastically different conclusions. We present their divergent findings to frame the broader discussion and situate our study within the larger debate on the true environmental impact of BEVs and ICEVs in the US (see Figure 4).

Forecasting the technological trends for new BEVs and ICEVs in 2025, Arthur. D. Little's modeling demonstrates that while the TCO differential between BEVs and ICEVs will decline significantly relative to 2015, ICEVs will continue to have an economic advantage ranging from $5,800 to $11,100 (Present Value) relative to BEVs. From an environmental perspective, the differentials in global warming potential and human toxicity potential will both widen in 2025 vis-a-vis 2015: BEVs will produce even lower levels of greenhouse gases relative to ICEVs, but they will generate approximately five times as much human toxicity potential compared to ICEVs due to the utilization of larger battery packs. Combined with the greater financial burden BEVs place on the consumer, the complex environmental reality of BEVs will continue to present challenges for the sustainability-minded consumer in choosing whether to drive a BEV or an ICEV.

Glossary of Acronyms

BEV Battery Electric Vehicle

CAFE Corporate Average Fuel Economy

CO2e Carbon Dioxide Equivalents

DALY Disability Adjusted Life Year

EPA Environmental Protection Agency

ESS Energy Storage System

FFDP Fossil Fuel Depletion Potential

FTP Freshwater Toxicity Potential

GWP Global Warming Potential

HEV Hybrid Electric Vehicle

HTP Human Toxicity Potential

ICEV Internal Combustion Engine Vehicle

kWh Kilo-Watt Hour

LCOE Levelized Cost of Electricity

MDP Mineral Depletion Potential

MWh Mega-Watt Hour

NERC North American Electric Reliability Corporation

NHTSA National Highway Traffic Safety Administration

OEM Original Equipment Manufacturer

p-DCB para-Dichlorobenzene

PHEV Plug-in Hybrid Vehicle

TCO Total Cost of Ownership

TTP Terrestrial Toxicity Potential

TVC True Vehicle Cost

1 Frankel, Todd C. The cobalt pipeline. Washington Post, September 30, 2016.

2 Whoriskey, Peter. In your phone, in their air. Washington Post, October 2, 2016.

3 Nealer, R.; Anair, D.; Reichmuth, D. Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions. Union of Concerned Scientists: Cambridge MA, 2015.

4 Holland, S.; Mansur, E.T..: Muller, N.; Yates, A. Environmental Benefits from Driving Electric Vehicles? National Bureau of Economic Research: Cambridge MA, 2015.

Summary of Findings

Arthur D. Little conducted a total lifecycle economic cost and environmental impact analysis of Lithium-ion battery electric vehicles (BEVs) versus internal combustion engine vehicles (ICEVs). The multifaceted results from this analysis include: 1) Total Cost of Ownership (TCO) representing the total lifecycle economic cost analysis, 2) Greenhouse Gas Emissions / Global Warming Potential (GWP) representing one aspect of the total lifecycle environmental impact analysis, and 3) Secondary Environmental Impacts representing another aspect of the total lifecycle environmental impact analysis. With respect to the environmental analysis and results, ADL determined that direct collateral impact to human life – defined by human toxicity potential, a secondary environmental impact – is an important consideration to be balanced against Greenhouse Gas Emissions / GWP in a comprehensive assessment of the relative environmental merits of BEVs and ICEVs.

- **Total Cost of Ownership (TCO)** – For a 2015 Compact Passenger Vehicle, the total cost of ownership over a twenty-year vehicle lifetime is $68,492 for the sample BEV model versus $47,676 for an equivalent ICEV—a 44% cost advantage for the ICEV excluding any government subsidies or incentives. For a 2015 Mid-Size Passenger Vehicle, the total cost to own a BEV is $85,854 versus $53,649 for the ICEV—a 60% cost advantage for the ICEV. The cost differential between BEVs and ICEVs will narrow for new vehicles in 2025.
- **Greenhouse Gas Emissions / Global Warming Potential (GWP)** – For a 2015 Compact Passenger Vehicle, the sample BEV model produces 105,054 pounds of greenhouse gas emissions (CO_2-equivalents) over a full vehicle lifetime, whereas the equivalent ICEV produces 136,521 pounds of greenhouse gas emissions, a 23% advantage in global warming potential for the BEV. For the 2015 Mid-Size Passenger Vehicle, the BEV produces 122,772 pounds of CO_2-equivalents, whereas the ICEV produces 151,651 pounds, a 19% advantage in global warming potential for the BEV. BEVs and ICEVs will both produce fewer greenhouse gas emissions in 2025, but the balance will still favor BEVs.
- **Secondary Environmental Impacts** – BEVs generate a host of secondary environmental impacts greater than those of ICEVs. A 2015 BEV generates enough toxicity over a vehicle's lifetime to cause an impact to human life equivalent to 20 days of life lost to death or disability,[5] whereas a 2015 ICEV generates enough toxicity to impact the average human life by only 6 days. The differential in secondary environmental impacts will widen for new vehicles in 2025, with BEVs producing even higher levels of human toxicity potential.

[5] Measured in disability adjusted life years (DALYs), a comprehensive metric defined by the National Institutes of Health as "the total number of years lost to illness, disability, or premature death within a given population.

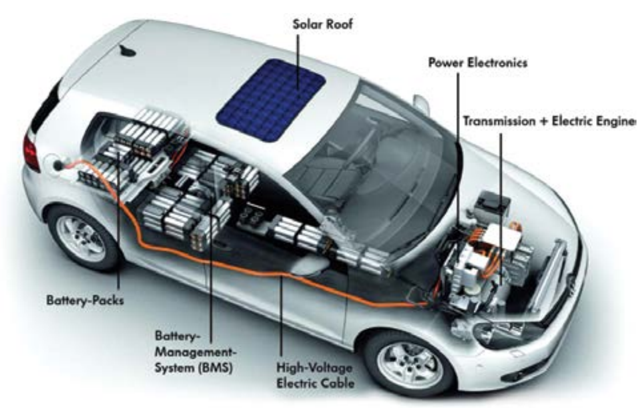
Introduction to BEVs

Today, the electric vehicle market in the United States is comprised of battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hybrid electric vehicles (HEVs). Alone among these vehicles, the BEV does not require gasoline at any point during operation, relying solely upon pure electric battery power (see Figure 5). This study focuses exclusively on the comparison between BEVs and Internal Combustion Engine Vehicles (ICEVs).

Of the other types of electric vehicles available in the US, the PHEV, like the BEV, uses a lithium-ion battery and runs on an electric motor, but the vehicle switches over to gasoline when the battery runs low. The HEV has an electric engine and powertrain but still runs on gasoline. HEV models, such as the ubiquitous Toyota Prius, have been available since 1999 in the US and over 4 million vehicles have been sold to date.

By contrast, BEVs have been available in the US mass market since December 2010, when the Nissan LEAF was introduced. Since the introduction of the Nissan LEAF, about 275,000 BEVs have been sold in the US. Year-on-year growth in BEV sales has been positive in every subsequent year, though the rate of growth has slowed in recent years (see Figure 6). This could be due to multiple factors, including a marked decline in the price of gasoline and the fact that BEVs are limited by driving range and a charging infrastructure that is still in a nascent stage of development.

Figure 5. Sample BEV Model



Source: Alternative Energy News

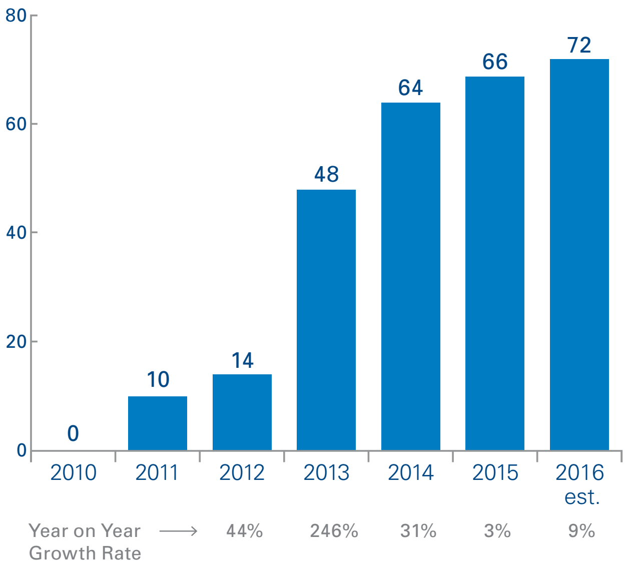
BEV sales also remain heavily concentrated in certain automotive segments and geographies. Roughly half of all BEVs sold in the US have been sold in California (see Figure 7). In addition, since 2014, over half of all BEVs sold in the US have been luxury models produced by Tesla. Further granulizing of this data reveals that about one quarter of all BEVs sold in the US have been luxury Tesla models sold in California. Of the remaining BEVs sold in the US, 45% have been Compact Passenger Vehicles. However, it is important to note that BEVs represent less than 1% of the entire US vehicle fleet today.

For the purposes of our assessment, ADL modeled two representative BEVs and their directly comparable ICEV counterparts – one for the Compact Passenger segment and one for the Mid-Size Passenger segment (see Figure 8). In order to assess the potential impact of widespread BEV adoption, we considered which vehicles were accessible to mass market consumers and imposed a $40,000 price threshold, thereby excluding the Luxury segment from the vehicle samples we used in constructing our models.

It is worth noting that the definitions of vehicle segments can vary by source, which has implications for the comparison between BEVs and ICEVs. For example, the classification system used by the EPA relies in large part on a vehicle's interior cubic footage, leading the EPA to classify the Nissan LEAF as a Mid-Size Passenger Vehicle. By contrast, most other mainstream sources (e.g. Car and Driver, Kelley Blue Book, etc.) treat the Nissan LEAF as a Compact Passenger Vehicle based on its specifications. Resultantly, it is important to consider the underlying features of a vehicle – as opposed to relying on the definition of vehicle segmentation from any one source – to ensure a true "apples-to-apples" comparison between BEVs and ICEVs.

Figure 6. Total US Sales of BEVs by Year

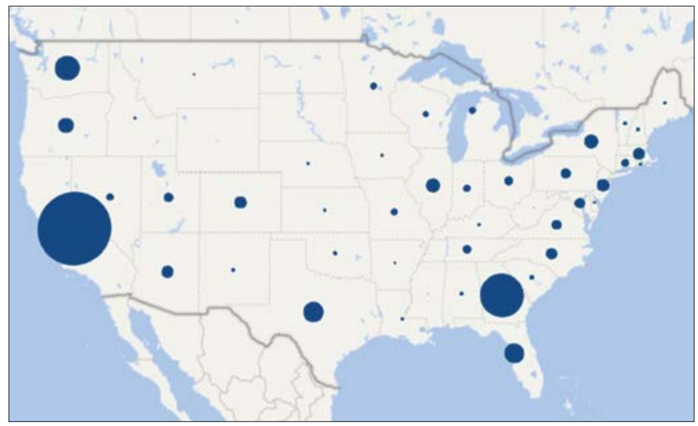
In Thousands



Source: ADL Analysis

Figure 7. Percentage of Total BEVs Sold in Each State in 2014

The size of each circle is proportional to the percentage of total BEV sales that each state represents.



Source: ADL Analysis

Figure 8. Sample Vehicles Used in the Study

Specifications - 2015	Compact Passenger	Mid-Size Passenger
BEV Battery Size – kWh	23	34
BEV Driving Range – Miles	76	100
BEV Efficiency – kWh per Mile	0.320	0.350
ICEV Reference Vehicle	Ford Focus Titanium	Honda Accord EX
ICEV MPG	30	27

Source: ADL Analysis

Economic Assessment: Total Cost of Ownership

ADL's study focused on two critical comparisons between BEVs and ICEVs – an economic assessment focused on Total Cost of Ownership (TCO), and an environmental impact analysis focused on GWP and Secondary Environmental Impacts. With regard to our TCO analysis, ADL decided to model the related economics of BEVs and ICEVs from the perspective of an individual consumer operating under real world conditions. To this end, it was necessary to ensure a true apples-to-apples cost comparison between BEVs and ICEVs.

One of the first adjustments we made was to account for the impact of BEV driving range. Survey data reveals that BEVs are driven an average of 27% fewer miles per year than comparable ICEVs, but BEV owners still travel the same total miles as their ICEV counterparts.[6] This phenomenon results from BEV owners using alternative modes of transportation for trips beyond the limited range of their BEVs – an issue for BEV owners that is further exacerbated by a lack of BEV charging infrastructure. We assigned the differential in miles driven between a BEV and an ICEV to a rental ICEV, reflecting the BEV owner's need for an alternative mode of transportation.

In our modeling for the BEV, we also made an adjustment to include the need for a replacement battery pack. Based upon the rate at which battery performance declines – which negatively impacts the range of a BEV – we estimated that the BEV battery pack would need to be replaced between years seven and ten of BEV's lifetime. This is consistent with the warranty that BEV manufacturers offer on their vehicles' battery packs. We note that the residual value of a BEV after 7-10 years may be less than the cost of a new battery pack which could result in salvaging the BEV instead of replacing the battery pack. However, in order to maintain a direct "apples-to-apples" comparison with ICEVs over a 20 year lifecycle, we modeled a battery pack replacement.

Furthermore, we removed the effect of federal and state incentives and subsidies on BEVs and ICEVs, so that our figures would reflect the true underlying costs of R&D, manufacturing, ownership and operation, and end-of-life of these vehicles. This included removing the state and federal tax component on gasoline price for ICEVs, because BEVs do not incur an equivalent tax burden.

Finally, we modeled each vehicle over a twenty-year vehicle lifetime and assumed that the total mileage traveled over that period is 150,685 miles. It is important to note that we also take "survivability" into account in our mileage figures (see Appendix B-2). In short, we adjust a vehicle's annual miles driven by the probability that the vehicle is still in use. Hence, while National Highway Traffic Safety Administration (NHTSA)data indicates that a vehicle will be driven approximately 7,500 miles in Year 20 of its lifetime, the data also indicates that only 9% of vehicles are still in operation after twenty years. Put another way, 91% of vehicles will have been permanently retired before reaching Year 20, and we have weighted our mileage figures to reflect this probability. To do otherwise would assume a fleet in which all vehicles continue to be driven for twenty years after entering the market, which is unrealistic given what we know about the true In-Use lifetime of vehicles in the U.S.

6 Based on data from The Idaho National Laboratory (INL) contained in their December 2014 report, "Plug-in Electric Vehicle Road Tax Analysis."

Total Cost of Ownership and True Vehicle Cost

To arrive at the comparative lifetime costs for BEVs and ICEVs, we used a measure called Total Cost of Ownership (TCO). TCO is comprised of two major cost categories: those incurred by the original equipment manufacturer (OEM) and those incurred once ownership of the vehicle has transferred to the consumer. TCO is a representation in dollars of how much owning a vehicle will cost over the lifetime of the vehicle, and it encapsulates all of the cost inputs incurred over the twenty-year lifecycle of a vehicle. For costs incurred before the transfer of ownership, we used a measure called Total Cost of Ownership (TCO). TVC encapsulates all of the cost inputs that go into making a vehicle, from designing, engineering, and manufacturing, as well as warranty cost and overhead, and results in the vehicle at the factory door. Once ownership has transferred to the consumer, costs include the In-Use costs of operating and maintaining the vehicle, and the end-of-life costs associated with disposing of the vehicle (see Appendix B for a full breakdown of TCO and TVC for the 2015 BEVs and ICEVs).

Our study concluded that BEVs were significantly more expensive to own and operate over the lifetime of a vehicle. For a 2015 Compact Passenger Vehicle, ADL found the BEV was 44% more expensive than an equivalent ICEV (see Figure 9). For a 2015 Mid-Size Passenger Vehicle, the cost impact differential was even more pronounced – the BEV was 60% more expensive than a comparable ICEV.

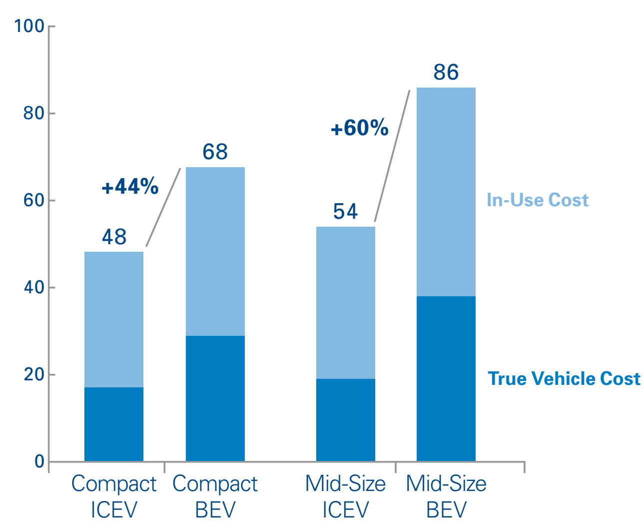
For the 2015 Compact Passenger Vehicle, TCO is $68,492 for the BEV versus $47,676 for the ICEV, and for the 2015 Mid-Size Passenger Vehicle, TCO is $85,854 for the BEV versus $53,649 for the ICEV over the lifetime of the vehicle (see Figures 10 and 11). Our cumulative TCO analysis demonstrates a significant BEV cost disadvantage throughout a vehicle's lifecycle and this cost disadvantage becomes even greater with the required battery pack replacement between years seven and ten of a BEV's lifetime.

These figures were driven by the underlying costs of manufacturing the vehicle: for BEVs, Total Vehicle Cost (TVC) was 70% higher for the 2015 Compact Passenger and 98% higher for the 2015 Mid-Size Passenger. For BEVs, TVC is the largest portion of TCO by far – breaking out the costs involved in producing a 2015 vehicle, TVC for the Compact Passenger BEV was nearly double that of the ICEV: $29,164 for the BEV and $17,146 for the ICEV (see Figure 12). For the Mid-Size Passenger, TVC for the BEV was $37,865 and $19,114 for the ICEV (see Figure 13). For the 2015 Compact Passenger BEV, the lithium-ion battery pack alone costs $6,900 to produce, accounting for a full 24% of the production costs associated with BEV manufacturing.

For In-Use costs, we developed a forecast for electricity and gasoline prices over a twenty-year vehicle lifetime, reflecting the costs associated with operating the vehicle, in order to ensure the accuracy of our TCO calculations (see Appendices B-3 and B-4). Electricity is forecast to be less expensive than gasoline on a per

Figure 9. Total Cost of Ownership over a 20-Year Lifetime for a 2015 ICEV versus an Equivalent BEV

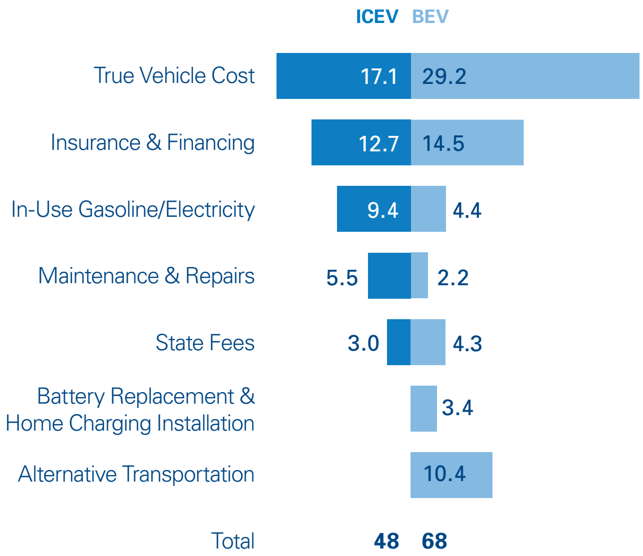
In Thousands of Dollars at Present Value



Source: ADL Analysis

Figure 10. Total Cost of Ownership over a 20-Year Lifetime for a 2015 Compact Passenger ICEV versus an Equivalent BEV

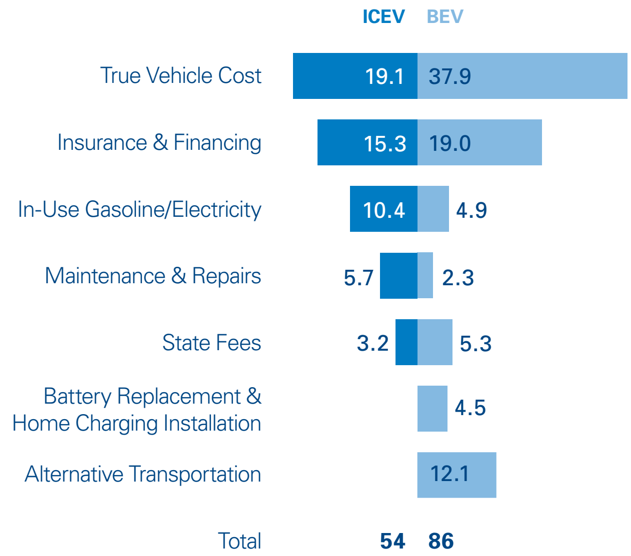
In Thousands of Dollars at Present Value



Source: ADL Analysis

Figure 11. Total Cost of Ownership over a 20-Year Lifetime for a 2015 Mid-Size Passenger ICEV versus an Equivalent BEV

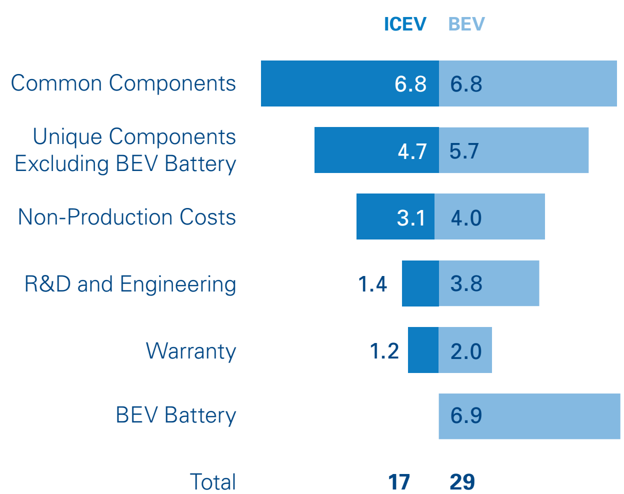
In Thousands of Dollars at Present Value



Source: ADL Analysis

Figure 12. True Vehicle Cost over a 20-Year Lifetime for a 2015 Compact Passenger ICEV versus an Equivalent BEV

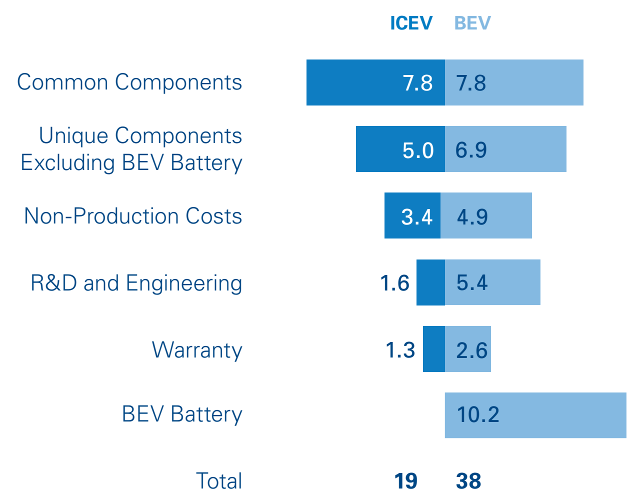
In Thousands of Dollars at Present Value



Source: ADL Analysis

Figure 13. True Vehicle Cost over a 20-Year Lifetime for a 2015 Mid-Size Passenger ICEV versus an Equivalent BEV

In Thousands of Dollars at Present Value



Source: ADL Analysis

mile basis and, in terms of In-Use costs, BEVs are cheaper to operate than their ICEV counterparts. However, this cost advantage was subsumed by other factors, such as the higher manufacturing costs for BEVs, and the BEV's need for a replacement battery pack and an alternative mode of transportation.

Ultimately, the high underlying cost of BEVs is a limiting factor in their future market penetration in the US automotive market. To date, BEVs represent less than 1% of US vehicle sales and fully one-quarter of BEV sales are Tesla models sold in California. In other words, Luxury vehicles sold within a limited geographic region represent approximately 25% of BEVs sold in the United States. If BEVs are to become truly competitive in the US, it will be imperative for manufacturers to reduce the heavy cost burden a BEV poses for the average consumer.

Environmental Assessment: Global Warming Potential

There is relatively little controversy surrounding how to measure the global warming potential (GWP) of ICEVs. Tailpipe emissions from gasoline combustion in an internal combustion engine combined with the upstream emissions associated with gasoline production and distribution contribute the majority of greenhouse gas emissions from an ICEV. A reliable range for such lifecycle emissions has been established by a preponderance of studies.

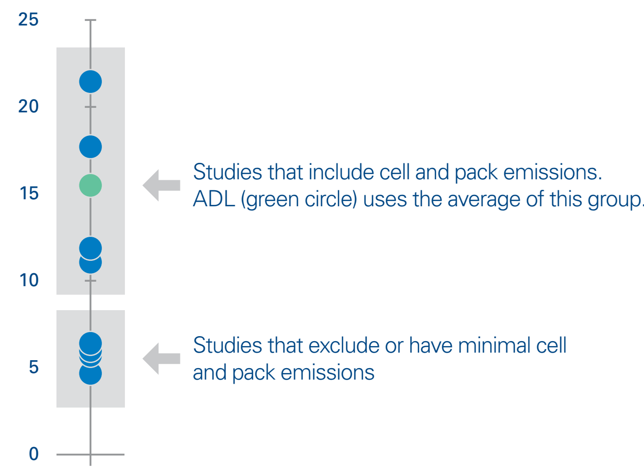
By contrast, BEVs present a unique challenge – though the vehicles produce no tailpipe emissions, BEVs do rely on regional power plants and grids to charge their batteries. Furthermore, R&D and manufacturing for BEVs relies heavily on a variety of different inputs – such as heavy metal mining and purification, and battery cell manufacture (which includes organic solvents and various chemical processes) – and these inputs generate different adverse environmental impacts as compared with those used in the R&D and manufacturing for ICEVs.

By far one of the more controversial aspects of GWP for BEVs is the production of the lithium-ion battery pack. In order to determine the impact this has on GWP for BEVs, we conducted a meta-analysis of studies that analyzed the greenhouse gas emissions generated by lithium-ion battery pack manufacturing (see Figure 14). It may appear that our assessment is on the higher end of studies that looked at GWP, but this discrepancy is mainly due to the fact that many studies do not include the impact of manufacturing battery cells into packs on overall GWP for battery manufacturing. This is an important consideration. By way of illustration, a paper put forward by Ford Motor Company analyzed the environmental impact of battery manufacturing for one of their vehicles.[7] For the 2014 Ford Focus BEV, the cells used in the battery were manufactured by LG Chem in their plant in Ochang, South Korea, and then shipped to a Piston Group facility in Michigan, where they were manufactured into packs. By

[7] Kim, H.C.; Ahn, S.; Arsenault, R.; Chulheung, B.; Lee, J.; Wallington, T.J. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis. Environ. Sci. Technol. 2016. 50 (22), 7715–7722.

Figure 14. GWP Emissions from Battery Manufacturing

In kg of CO_2e Emissions per kg of Battery Weight



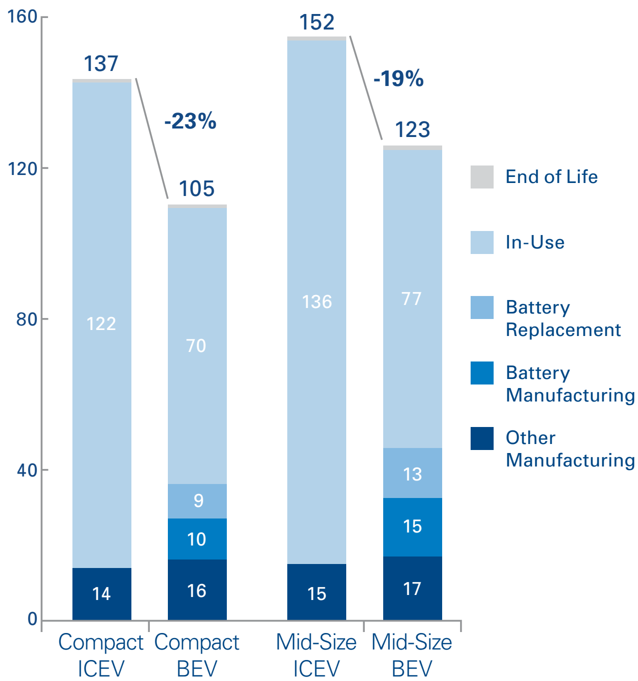
Source: ADL Analysis

not fully including the GWP generated in the pack manufacturing stage, other studies have ignored the emissions from a crucial stage in battery manufacturing. ADL chose to utilize a value that was an average of the published, peer-reviewed studies that included battery pack manufacturing in their analyses.

Another critical point when measuring GWP centers on emissions generated by power plant which produce the electricity necessary for charging BEVs. Depending on where a BEV is driven, the local power grid energy mix may have a greater or lesser environmental impact. In conducting our analysis, ADL weighted the electricity demand generated by the BEV fleet according to the geography in which BEVs are being sold. We constructed a twenty-year forecast of the US energy mix by NERC region, aligning with a twenty-year vehicle lifetime. Our US energy mix forecast takes into account the goals set by the US Clean Power Plan (see Appendix C-2 for greater detail on GWP from electricity generation). It is worth

Figure 15. Emissions over a 20-Year Lifetime for a 2015 ICEV versus an Equivalent BEV

In Pounds of CO_2 Emissions



Source: ADL Analysis

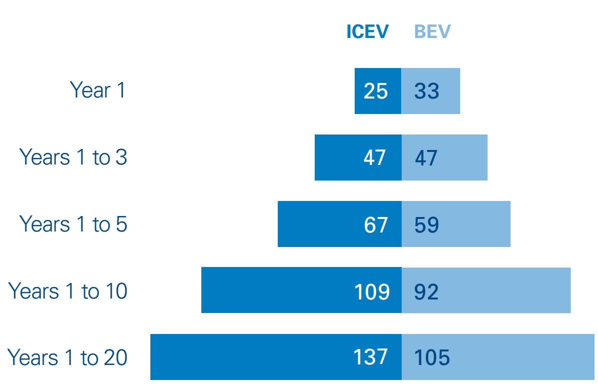
remembering that the largest number of BEVs are currently being sold in California, which has a relatively low carbon-intensity for power grid electricity generation. If BEV sales followed a similar nationwide sales pattern to ICEVs, their GWP impact would be approximately 3% greater, in absolute terms, than the 2015 BEV-sales weighted BEV-ICEV GWP differentials.

ADL concluded that lifecycle GWP was approximately 23% lower for a Compact Passenger BEV and 19% lower for a 2015 Mid-Size Passenger BEV compared with equivalent ICEVs (see Appendix C for a full breakdown of GWP for the 2015 BEVs and ICEVs). The difference between 23% for a Compact Passenger BEV and 19% for a Mid-Size Passenger BEV is nearly fully attributable to the larger battery pack in the Mid-Size Passenger BEV. On a per mile basis, BEVs have lower GWP over a twenty-year vehicle lifetime, but this is offset by the fact that GWP from manufacturing is twice as large for BEVs. This is, again, largely due to the lithium-ion battery packs, which produce 10,326 pounds of CO_2-equivalents for the 2015 Compact Passenger BEV and 15,264 pounds of CO_2-equivalents for the 2015 Mid-Size Passenger BEV (see Figure 15).

As a result of the effect of manufacturing, BEVs have a larger total GWP over the first three years of a vehicle's lifetime, but their lower In-Use emissions offsets this effect by the end of year three (see Figure 16). Given that 75-85% of all BEVs

Figure 16. GWP Emissions from a 2015 Compact Passenger ICEV versus an Equivalent BEV at Different Stages of Vehicle Life

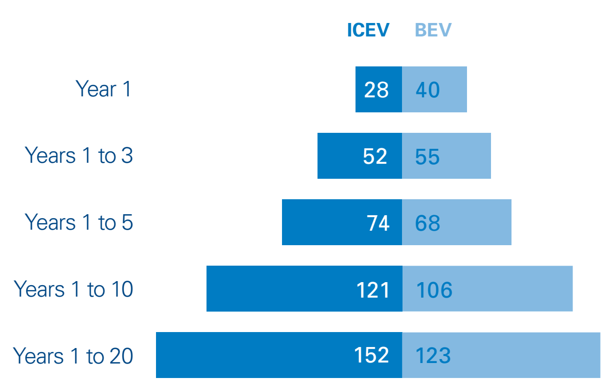
In Pounds of CO_2e Emissions



Source: ADL Analysis

Figure 17. GWP Emissions from a 2015 Mid-Size Passenger ICEV versus an Equivalent BEV at Different Stages of Vehicle Life

In Pounds of CO_2e Emissions



Source: ADL Analysis

(excluding Tesla) have been leased and the average BEV lease is 3 years, first leasees of BEVs are contributing to GWP a near identical amount as ICEV owners or leasees. As the US energy mix shifts from conventional sources to renewables and increased natural gas, CO_2-equivalent emissions will decline in coming decades. This means that, in ADL's analysis, the energy mix shifts to grant an increasing incremental benefit to BEVs as a vehicle's lifetime progresses.

For the 2015 Compact Passenger Vehicle, the BEV produces 105,054 pounds of CO_2-equivalents, whereas the ICEV produces 136,521 pounds of CO_2-equivalents. For the 2015 Mid-Size Passenger Vehicle, the results are similar but less favorable for the BEV. Over a twenty-year vehicle lifecycle, the BEV produces 122,772 pounds of CO_2-equivalents, whereas the ICEV produces 151,658 pounds of CO_2-equivalents.

Environmental Assessment: Secondary Environmental Impacts

In addition to global warming potential, there are a host of other environmental impacts that arise from the manufacturing and operation of BEVs and ICEVs. The direct impact on human, terrestrial, and aquatic life, as well as the relative depletion of natural resources: these are all important concerns, which must be weighed against the overall reduction in global warming potential associated with BEVs.

In order to conduct a truly comprehensive assessment of the environmental impact of BEVs and ICEVs, we examined five secondary environmental impacts for both types of vehicle: human toxicity potential (HTP), terrestrial toxicity potential (TTP), freshwater toxicity potential (FTP), mineral depletion potential (MDP), and fossil fuel depletion potential (FFDP). These secondary environmental impacts are defined as follows:

- Human Toxicity Potential (HTP) is a calculated index that reflects the potential harm to humans from a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and also its potential dose.
- Freshwater Toxicity Potential (FTP) is a calculated index that reflects the potential harm to freshwater organisms from a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and also its potential dose.
- Terrestrial Toxicity Potential (TTP) is a calculated index that reflects the potential harm to terrestrial organisms from a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and also its potential dose.
- Mineral Depletion Potential (MDP) is a measure of consumption of natural resources, specifically those that are mined, expressed in grams of iron-equivalents.
- Fossil Fuel Depletion Potential (FFDP) is a measure of consumption of fossil fuels, expressed in grams of oil-equivalents.

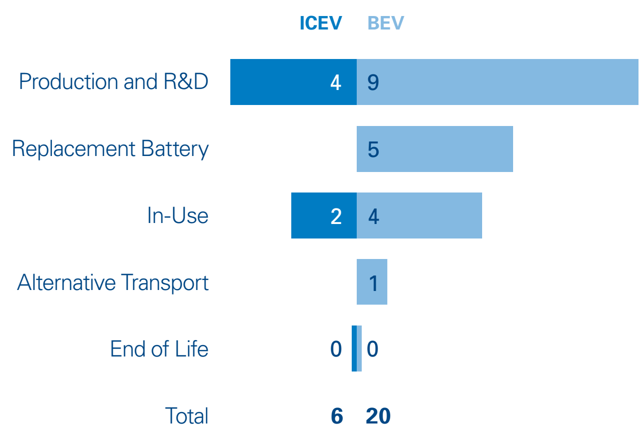
As with GWP, to measure each of these impacts we conducted a full Life Cycle Assessment – beginning with the sourcing of raw materials, through R&D, manufacturing and In-Use, to the ultimate disposal of the vehicle – and we determined the impact of each input at each stage for the BEV and the equivalent ICEV. In conducting this assessment, we leveraged the methodology defined by Troy Hawkins et al. in "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles."[8]

For the three toxicity indices we calculated – HTP, TTP, and FTP – we determined the amount of toxic byproducts generated by each input to the vehicle, and we then converted these estimates into equivalent units of *p*-DCB, a standard measure for toxicity. This enabled us to combine all of the different toxicity impacts generated across a vehicle's lifecycle into a single lifetime toxicity index. For human toxicity potential (HTP), we took an additional step and expressed the impact of our *p*-DCB measure in disability adjusted life years (DALYs), using the conversion rates provided by the USEtox model of the United Nations Environment Program (UNEP). One DALY is equivalent to a year of healthy life lost to mortality or morbidity.

We found that over a twenty-year vehicle lifetime, a 2015 BEV generates enough human toxicity potential to impact human health by 20 days lost to death or disability, while a 2015 ICEV generates enough human toxicity potential to impact the average human life by 6 days. Simply put, manufacturing BEVs generates significantly more toxicity to human health than manufacturing ICEVs: ADL's study determined that a BEV generated more than three times as much human toxicity over its lifetime as an equivalent ICEV (see Figure 18). Battery pack manufacturing and more specifically human exposure to heavy metals such as cobalt and nickel in addition to graphite during the mining process accounts for the vast majority of human toxicity potential of BEVs.

[8] Hawkins, T.R.; Majeau-Bettez, G.; Singh, B.; Strømman, A.H. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 2012. 17 (1), 53-64.

Figure 18. Days of Life Impact (Death or Disability) for a 2015 Compact Passenger ICEV versus an Equivalent BEV over 20 Years of Ownership



Values do not sum to total due to rounding. Source: ADL Analysis

Once the types of pollution generated by the US power grid are taken into account (e.g. tailings from coal power plants), BEVs generate twice as much human toxicity potential for the In-Use portion of a vehicle's environmental lifecycle compared to the In-Use portion of an ICEV (see Figure 18).

The In-Use portion of ICEV lifecycle accounted for 34.5% of the human toxicity generated by the vehicle, while the In-Use portion of BEV lifecycle only accounted for 19% of the human health impact caused by the vehicle. The largest portion of impact for the BEV came from manufacturing, accounting for 44% to 45% (depending on the type of battery used) of the vehicle's total human toxicity impact, with the battery replacement accounting for an additional 30% to 31%.

Across all of the other secondary environmental impacts ADL measured – except for FFDP – the BEV performed similarly or worse than the ICEV. BEVs generated more than twice as much freshwater toxicity potential and BEVs were responsible for nearly twice as much mineral depletion, owing to the use of heavy metals in the manufacturing process for BEVs (see Appendix D for greater detail). Nonetheless, neither BEV manufacturing nor ICEV manufacturing poses a threat to the global supply of mineral resources.

All other secondary environmental measures pale in comparison with the potential impact BEVs have on human health. Because human toxicity potential is distributed differently across a vehicle's lifetime, the decision to drive a BEV instead of an ICEV essentially shifts the damage to human life caused by car ownership, from a relatively small impact more localized to the vehicle in the case of an ICEV, to a relatively large impact localized to the mineral mine tailings in the case of a BEV. For the American driver, the decision becomes a trade-off between generating small amounts of pollution in one's local community (or driving region) versus generating comparatively large amounts of pollution in regions where mining and manufacturing occur.

Ultimately, our assessment of secondary environmental impacts demonstrates that BEVs do achieve the goal of reducing GWP by the third to fourth year of the vehicle's life, but they do so at a cost. The production of lithium-ion battery packs creates more damaging pollution to human life than ICEVs generate over the course of a vehicle's lifetime. This collateral impact to human life is an important consideration to be balanced against greenhouse gas emissions in a comprehensive assessment of the relative environmental merits of BEVs and ICEVs.

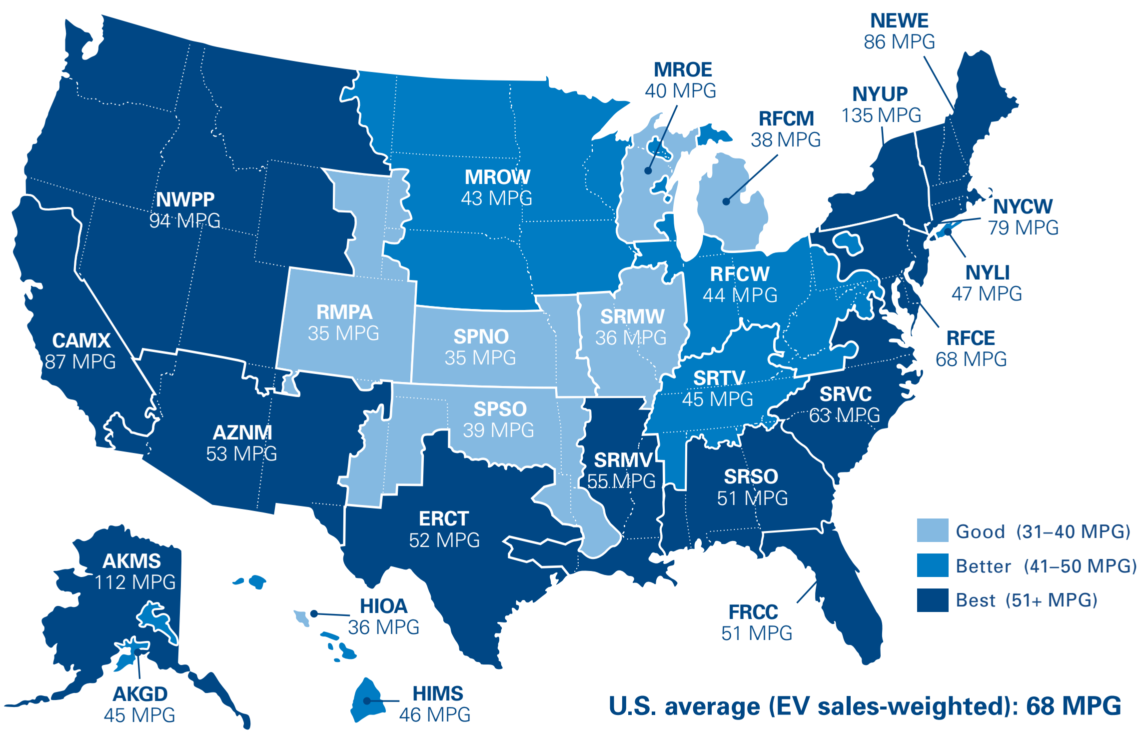
Alternative Views

Arthur D. Little conducted a meta-analysis of other studies that examined the environmental impact of BEVs and ICEVs. In this section, we present a summary and discussion of two widely-cited reports: "Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Global Warming Emissions,"[9] from the Union of Concerned Scientists (UCS), and "Environmental Benefits from Driving Electric Vehicles?"[10] from the National Bureau of Economic Research (NBER). Both of these reports examine the environmental impact of BEVs and ICEVs, and both reports describe the policy implications that arise from their findings. However, UCS and NBER reach drastically different conclusions. Arthur D. Little presents the divergent findings of these reports to frame the broader discussion and situate our

[9] Nealer, R.; Anair, D.; Reichmuth, D. Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Lifetime Global Warming Emissions. Union of Concerned Scientists: Cambridge MA, 2015.

[10] Holland, S.; Mansur, E.T..: Muller, N.; Yates, A. Environmental Benefits from Driving Electric Vehicles? National Bureau of Economic Research: Cambridge MA, 2015.

Figure 19. Electric Vehicle Global Warming Pollution Ratings and Gasoline Vehicle Emissions Equivalents by Electricity Grid Regions

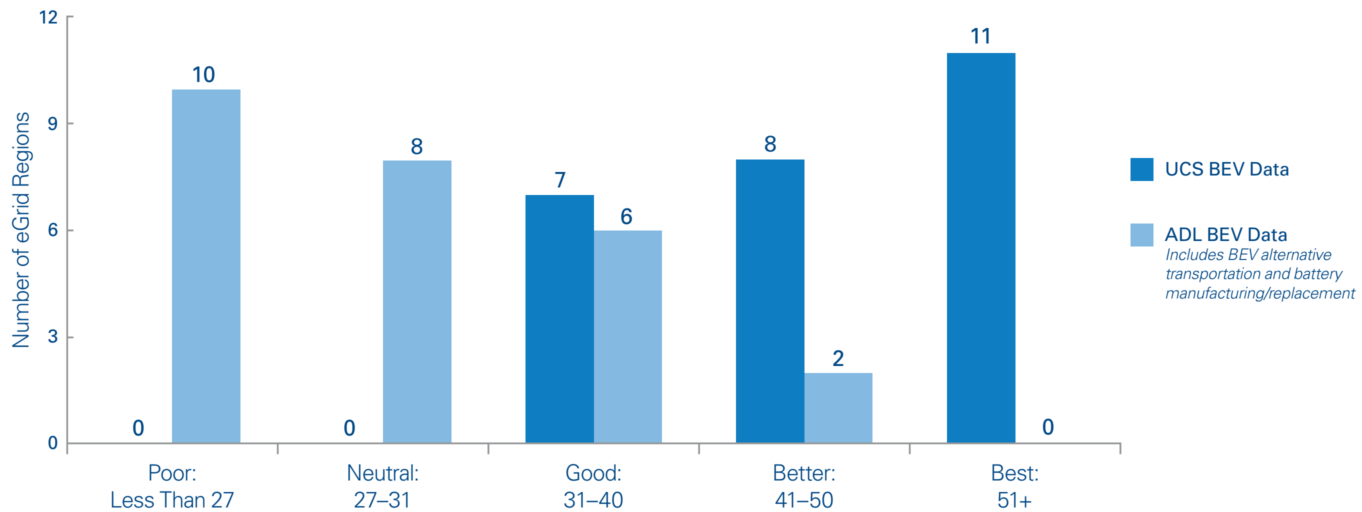


Note: The MPG (miles per gallon) value listed for each region is the combined city/highway fuel economy rating of a gasoline vehicle that would have global warming emissions equivalent to driving an EV. Regional global warming emissions ratings are based on 2012 power plant data in the EPA's eGRID 2015 database (the most recent version). Comparisons include gasoline and electricity fuel production emissions. The 68 MPG U.S. average is a sales-weighted average based on where EVs were sold in 2014.

Source: EPA 2015C; IHS 2015.

Figure 20. UCS Map with ADL Adjustments for Battery Manufacturing, Battery Replacement, and Alternative Transportation

In MPG Equivalent Range



Source: ADL Analysis

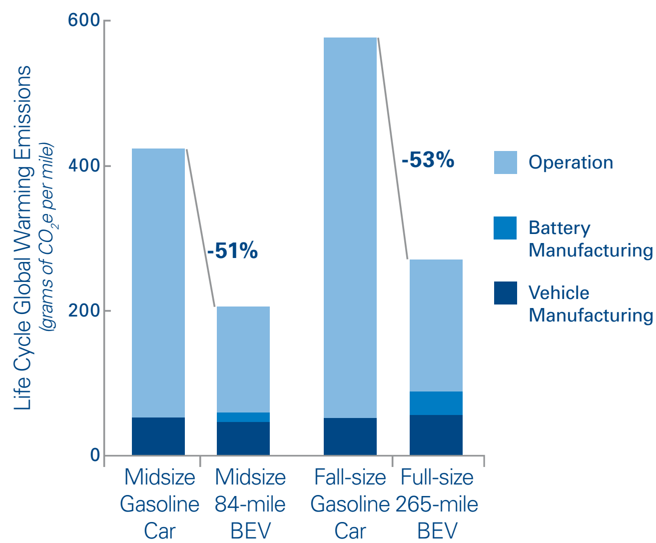
findings within the debate on the true environmental impact of BEVs and ICEVs in the US.

"Cleaner Cars from Cradle to Grave"

There are two primary conclusions espoused by the Union of Concerned Scientists (UCS) in their report, "Cleaner Cars from Cradle to Grave: How Electric Cars Beat Gasoline Cars on Global Warming Emissions." First, the authors conclude that BEVs generate only half the greenhouse gas emissions of ICEVs. Secondly, the authors argue that BEVs are cleaner than ICEVs no matter where in the US they are driven (see Figure 19). These conclusions differ from ADL's findings (see Figure 20).

UCS arrived at these conclusions by conducting an environmental Life Cycle Assessment of two composite BEVs and equivalent ICEVs, comparing the lifetime greenhouse gas emissions produced by each. UCS took into account the emissions generated by vehicle manufacturing for BEVs and ICEVs, and compared the emissions produced by combusting gasoline to run ICEVs with the emissions generated by power plants when BEVs are run on electricity drawn from regional power grids. UCS found that vehicle manufacturing produces higher greenhouse

Figure 21. Life Cycle Global Warming Emissions from the Manufacturing and Operation of Gasoline and Battery-Electric Vehicles



Source: ADL Analysis

gas emissions for BEVs, in large part due to the production of the lithium-ion battery pack, but BEVs produce half as much greenhouse gas emissions over a vehicle's lifetime, owing to the higher emissions generated by ICEVs once the vehicles are placed in operation (see Figure 21).

To determine BEV emissions, UCS segmented the country into regional electricity grids according to the EPA's eGRID database and used the power mix for each region to determine the emissions generated by running a BEV on electricity generated in that region. UCS then converted the BEV emissions into an equivalent MPG number, based on the emissions produced by the vehicle for each mile traveled. Finally, UCS ranked each region according to the regional greenhouse gas emissions generated by operating a BEV there (see Figure 19). Under this method, there was not a single region in which ICEVs produced lower greenhouse gas emissions than BEVs. While approximately a third of the country by area falls in one of the "Best" regions ranked by UCS, these regions actually represent approximately two-thirds of the national population.

For the purposes of their study, UCS modeled two BEVs—one based on the Nissan LEAF and the other on the Tesla Model S, the two best-selling BEVs in the US market today. UCS compared these vehicles to a composite Mid-Size Passenger ICEV and Full-Size Passenger ICEV, respectively, and assumed the ICEVs would be driven for the same lifetime miles as their BEV counterparts. This involved adjusting Mid-Size Passenger ICEV lifetime miles downward according to survey data that indicates Mid-Size Passenger BEVs are driven fewer miles annually. For the BEVs, UCS assumed each vehicle would use one battery over its lifetime and the energy mix in each region would remain constant over the lifetime of the vehicle. The UCS data for lifetime emissions was drawn from the GREET model developed and maintained by Argonne National Laboratory.

Based on their findings, UCS offers a number of policy recommendations, urging Congress to continue funding research into lithium-ion battery development and recycling, and to maintain the $7,500 federal tax credit for BEV purchases. They furthermore conclude, "together with other oil-saving approaches, such as more efficient vehicles and advanced biofuels, EVs can help cut projected US oil use in half over the next 20 years."

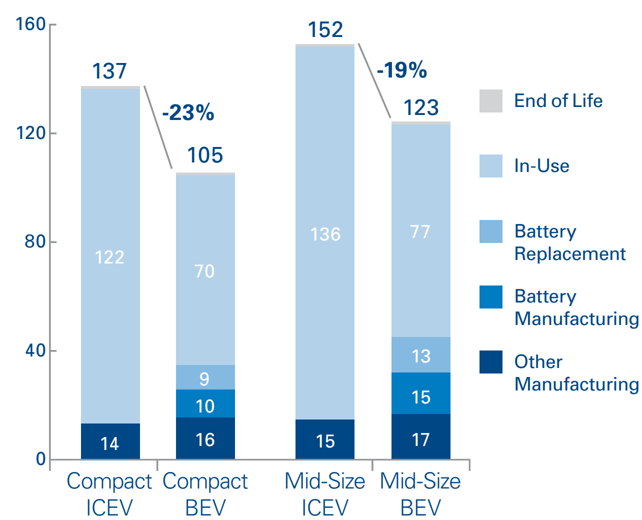
Over the course of a vehicle's lifetime, ADL and UCS are aligned in concluding that BEVs decrease global warming potential compared with equivalent ICEVs. However, the conclusions of ADL's study are markedly different from UCS' in the magnitude of the reduction of CO_2-equivalents: UCS calculates the reduction at approximately 50%, while ADL's results reveal that this reduction is approximately 20% (see Figure 22). While there are many aspects of ADL's and UCS' analyses that are fundamentally aligned, there are variances that stem from our divergent perspectives. In order to make a balanced, "apples-to-apples" comparison, ADL modeled a number of real world factors encountered by consumers, such as the need for alternative transportation, battery replacement, vehicle survivability, etc., while UCS's study is more akin to a "laboratory test" of vehicle emissions under controlled circumstances (see Figure 23). These differences lead to a dramatic change in the GWP calculations for new 2015 BEVs as calculated by ADL versus UCS.

"Environmental Benefits from Driving Electric Vehicles?"

The conclusion reached by a team from the National Bureau of Economic Research in their working paper, "Environmental Benefits from Driving Electric Vehicles?," is that – depending on where the vehicle is driven – driving a BEV may actually cause more widely-dispersed and damaging emissions than driving a similar ICEV. Using a monetized environmental benefit measure, NBER determined that the welfare maximizing national subsidy

Figure 22. Emissions over a 20-Year Lifetime for a 2015 ICEV versus an Equivalent BEV

In Pounds of CO_2 Emissions



Source: ADL Analysis

on BEVs would be -$742. In other words, owing to the greater environmental impact caused by BEVs compared to ICEVs, the NBER study implies that the current federal subsidy for BEVs should be replaced with a national tax on BEVs (see Figure 24).

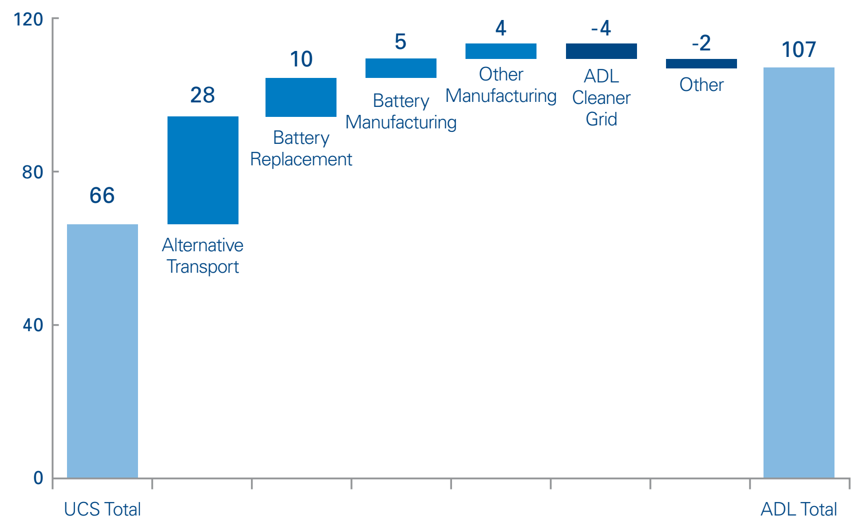
NBER reached this conclusion using the AP2 Model, "an integrated assessment model that links emissions of air pollution to exposures, physical effects, and monetary damages in the contiguous United States" (see Figure 25). NBER examined the impact of BEVs and ICEVs on global warming, as well as the environmental impact of a host of local pollutants. In the NBER model, the main environmental impact of BEVs came from the power plants that supplied the electricity used to charge the vehicles.

Based on the county in which a BEV was charged, NBER determined the grid and power plants that supplied it with electricity, and then estimated the resulting emissions from these power plants. As a result of the interconnectivity of the US power grid and the drift of pollutants, NBER found that BEVs had a much more widely-dispersed environmental impact, spread across hundreds of miles.

NBER monetized the environmental impacts according to the effect that these emissions had on a number of "welfare endpoints," such as human health and non-human factors like agriculture and building degradation. NBER looked at the damage costs of local pollutants generated by BEVs on a regional level using the power grid regions defined by the North American Electric Reliability Corporation (NERC). Ultimately, NBER concluded that ICEVs have a greater cost impact in terms of CO_2-equivalents, but BEVs have a greater cost

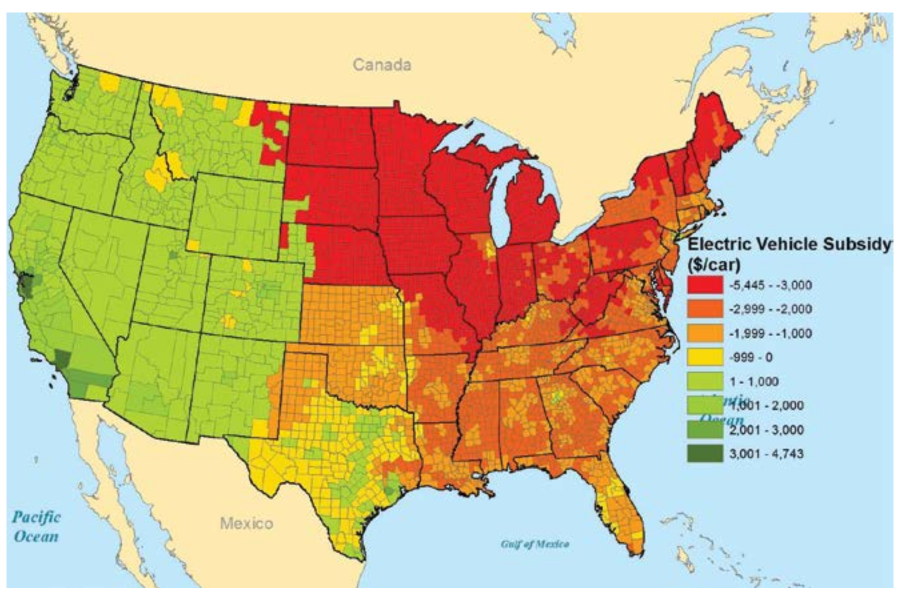
Figure 23. Drivers of the Difference between Emissions Estimates for ADL's 2015 Compact BEV and UCS' 2015 Nissan LEAF

In Thousands of Pounds of CO_2 Emissions



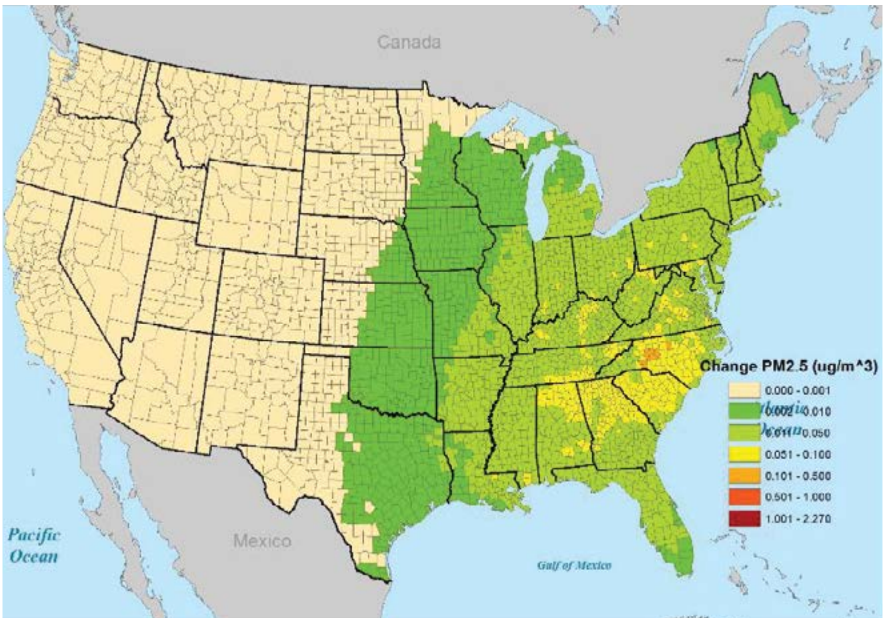
Source: ADL Analysis

Figure 24. Second-Best Electric Vehicle Subsidy by County



Source: National Bureau of Economic Research

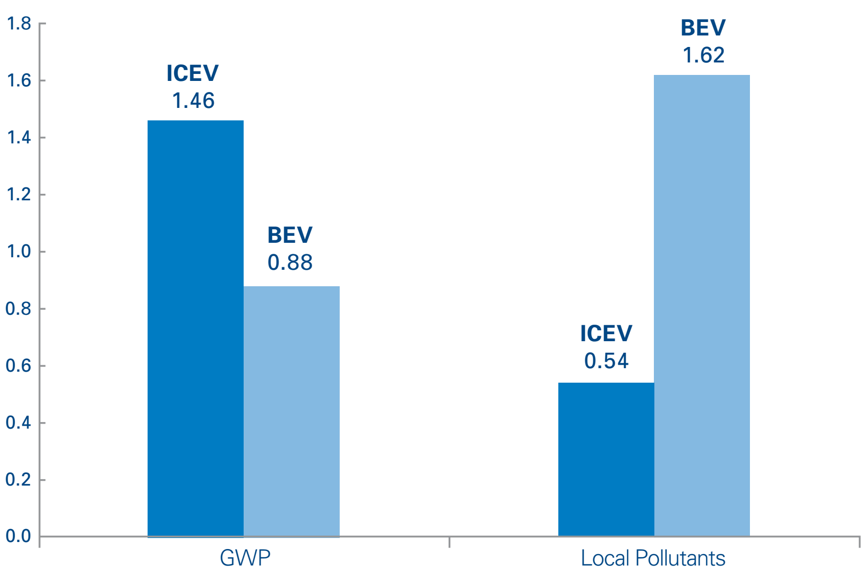
Figure 25. Change in PM2.5: 1000 BEV Focus in SERC Region (Emissions for a BEV Ford Focus Driven in Fulton County, GA)



Source: National Bureau of Economic Research

Figure 26. Estimated Impact of an ICEV versus a BEV: GWP and Local Pollutants

In Cents per Mile



Source: ADL Analysis of National Bureau of Economic Research Findings

impact in terms of local pollutants. In sum, however, driving a BEV had a total cost impact of $2.50 per mile driven compared with $2.00 for an ICEV in terms of marginal damages (see Figure 26). These figures do not include the full lifecycle of the vehicle; NBER only examined the In-Use portion of a vehicle's lifecycle.

For the purposes of their study, NBER modeled the BEV and ICEV models of the Ford Focus. NBER assumed the BEV and ICEV would be driven for the same lifetime miles, but they adjusted the kilowatt-hours consumption of the BEV to reflect the impact of extreme weather on battery performance. NBER assumed the BEV would use one battery over its lifetime and the energy mix in each region would remain constant over the lifetime of the vehicle.

NBER monetized their assessment of local pollutants using peer-reviewed studies on the impacts of each pollutant. Impacts were estimated per county and, for human health impacts, these figures took into account population age and density. Mortality costs were determined by looking at lives that would have been shortened due to pollution exposure and assigning a dollar value to this impact using a Statistical Value of Life of $6 million. For carbon emissions, NBER used the EPA figure for the social cost of carbon—$42 per ton.

Ultimately, NBER concluded that "public policy evaluation is especially difficult and important" when it comes to situations such as the federal subsidy for BEVs, necessitating the development of complex models that capture the many dimensions of environmental impact. Under their model, NBER concluded that BEVs have a net negative effect in terms of environmental impact compared with ICEVs.

Technology Forecast: BEVs and ICEVs in 2025

Given that BEV technology development is still advancing and the public charging infrastructure remains in a nascent stage, many of the factors presented in our 2015 assessment are likely to change over time. Already, in 2016, General Motors has announced plans to bring the Chevrolet Bolt to market by the end of the year. The Chevrolet Bolt is a BEV with a 60 kWh battery, a vehicle range of 238 miles, and an MSRP of $37,495. Such a vehicle drastically alters the picture for BEVs compared with 2015, greatly reducing the need for alternative transportation but also (presumably) greatly increasing the environmental impact of battery manufacturing.

If the cost per kWh and environmental impacts of lithium-ion batteries decline, this would also radically alter the overall picture for BEVs. Over time, the US energy mix for electricity generation will continue to shift from conventional sources to renewables and increased natural gas in order to achieve emissions targets set by policymakers. Likewise, ICEV technology will continue to evolve, owing to more stringent fuel efficiency standards.

To account for these future technology developments, ADL constructed a forecast of technology trends and their related economic and environmental impacts. ADL's forecast was used to assess the impact of all the inputs utilized in our 2015 assessments for new vehicles in 2025 (see Appendix E for greater detail on projected technology trends).

As we head to 2025, lithium-ion battery cost per kWh and CO_2-equivalents remain the dominant factor influencing the TCO and environmental analyses. Since the launch of BEVs in the US in 2010, the cost of producing battery packs has decreased by approximately 70%. ADL projects that the cost per kilowatt-hour of lithium-ion battery packs will be reduced a further 60% by 2025, dropping to $120 per kWh, which is consistent with current battery manufacturer forecasts (see Appendix E-1).

ADL projects that the density of batteries will also improve, enabling lighter batteries to provide a greater driving range to the BEV. Based upon our analysis of technology trends, our economic and environmental forecasts, and our interviews with select OEMs, ADL projects manufacturers of BEVs will take advantage of these developments to increase battery pack size and thus extend BEV range (as seen with the Chevrolet Bolt, OEMs are

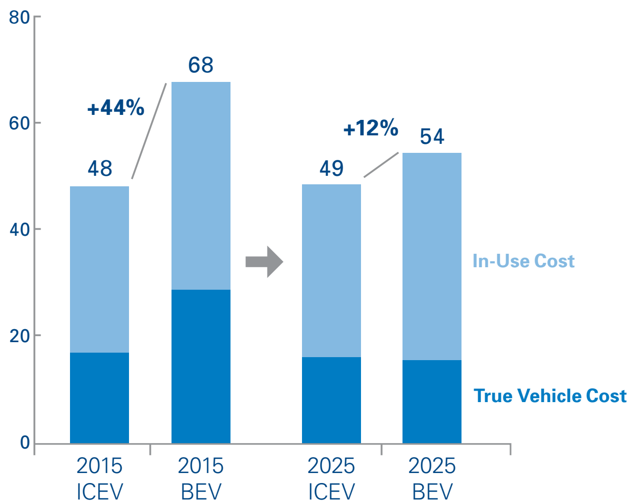
Figure 27. Forecast Key Specifications for 2025 Vehicles

Specifications - 2025	Compact Passenger	Mid-Size Passenger
BEV Battery Size – kWh	50	67
BEV Driving Range – Miles	250	300
BEV Efficiency – kWh per Mile	0.211	0.230
ICEV MPG	40	36

Source: ADL Analysis

Figure 28. Total Cost of Ownership over a 20-Year Lifetime for a Compact ICEV and an Equivalent BEV, 2015 versus 2025

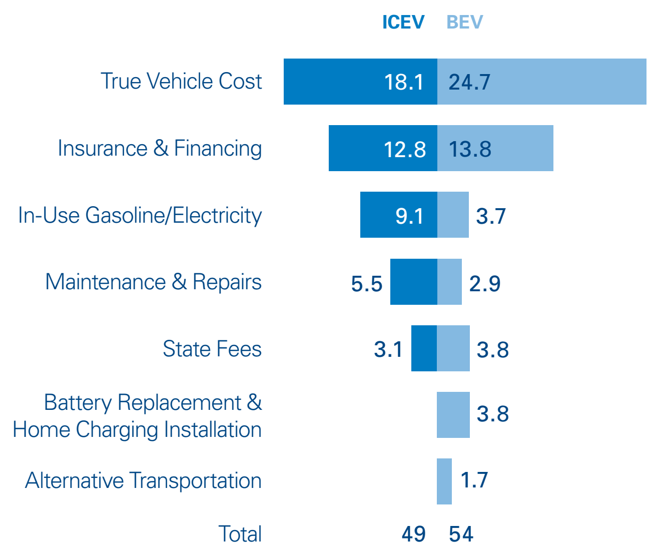
In Thousands of Dollars at Present Value



Source: ADL Analysis

Figure 29. Total Cost of Ownership in Thousands of Dollars over a 20-Year Lifetime for a 2025 Compact Passenger ICEV versus and Equivalent BEV

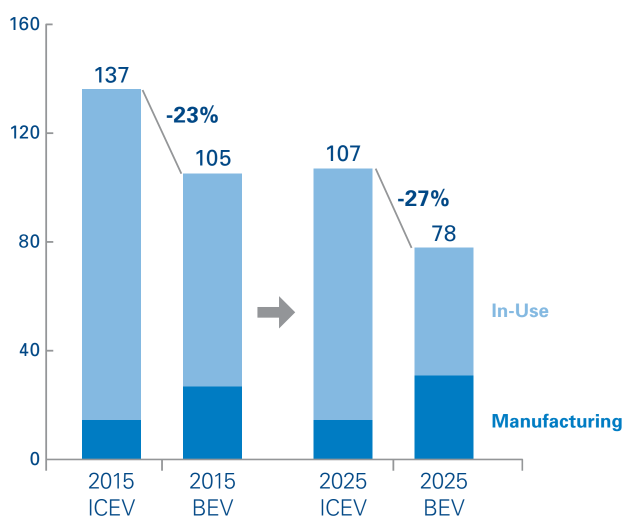
In Thousands of Dollars at Present Value



Source: ADL Analysis

Figure 30. Emissions of CO_2e from a Compact Passenger ICEV Compared to an Equivalent BEV, 2015 versus 2025

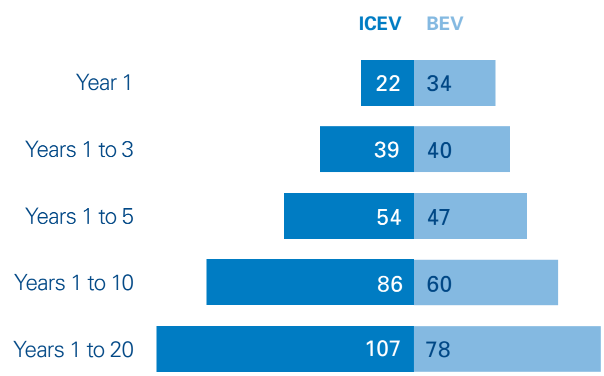
In Thousands of Pounds of CO_2e Emissions



Source: ADL Analysis

Figure 31. GWP Emissions from a 2025 Compact Passenger ICEV versus an Equivalent BEV at Different Stages of Vehicle Life

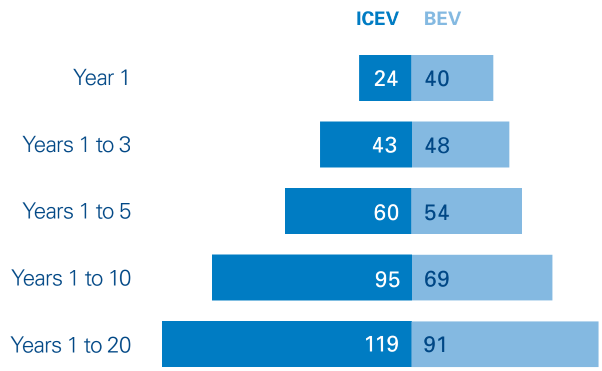
In Pounds of CO_2e Emissions



Source: ADL Analysis

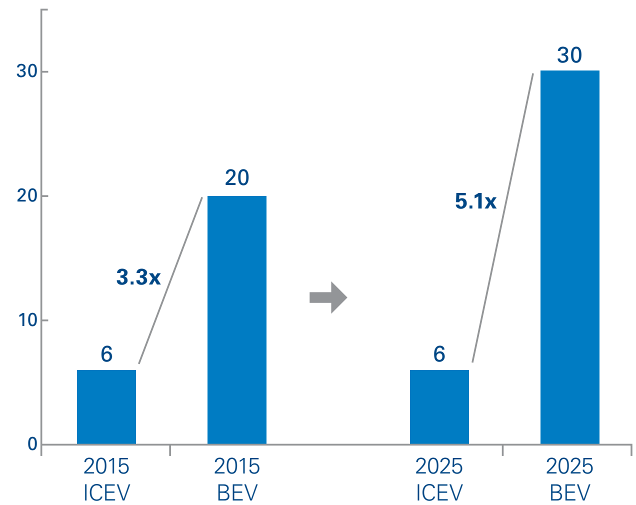
Figure 32. GWP Emissions from a 2025 Mid-Size Passenger ICEV versus an Equivalent BEV at Different Stages of Vehicle Life

In Pounds of CO_2e Emissions



Source: ADL Analysis

Figure 33. Days of Life Impact (Death or Disability) for a Compact Passenger ICEV versus an Equivalent BEV over 20 Years of Ownership, 2015 versus 2025



Source: ADL Analysis

already increasing battery pack size dramatically to improve BEV range). The impacts of these developments will offset many of the GWP and TCO benefits of battery technology improvements. Furthermore, the need for alternative transportation for BEV owners will be reduced. The overall effects of these changes are likely to have important implications for the TCO, GWP, and Secondary Environmental Impacts of BEVs (see Appendix E-2 for greater detail on the results of our 2025 modeling).

Meanwhile, ICEVs will become more costly to produce, as manufacturers invest in a host of technological modifications to meet more stringent CAFE (Corporate Average Fuel Economy) standards. Many of these modifications – such as lighter vehicle bodies – will also apply to BEVs, helping to reduce their environmental impact as well. Given that CAFE standards are assessed on the vehicle fleet as a whole, improvements in ICEV fuel efficiency will only go so far, as the need for further ICEV modifications will be offset by a portfolio weighted more heavily toward hybrid vehicles and BEVs.

ADL's technology trends forecast will impact the magnitude of the TCO, GWP and secondary environmental impact differentials between BEVs and ICEVs (see Figure 27 for forecast key specifications for 2025 vehicles). Despite a significant narrowing in TCO variance between BEVs and ICEVs due to these developments, ICEVs will still retain their TCO advantage. The TCO for a 2025 Compact Passenger will be 12% greater for the BEV than for the ICEV, and for the 2025 Mid-Size Passenger the TCO will be 20% greater for the BEV than for the ICEV (see Figures 28 and 29). Meanwhile, even as ICEVs adapt to CAFE standards and battery pack size increases for BEVs, BEVs will expand their advantage in GWP. The 2025 Compact Passenger BEV will have a 27% GWP advantage over the ICEV (see Figure 30). The 2025 Mid-Size Passenger BEV will have a 23% GWP advantage.

Results from analyses of CO_2-equivalents emissions at various stages of a vehicle's lifetime are similar between 2015 vehicles and 2025 vehicles. More specifically, at the end of year 3, ADL forecasts a 2025 Compact Passenger BEV will generate approximately 1,700 more pounds of CO_2-equivalents than the comparable ICEV (Figure 31) while a 2025 Mid-Size Passenger BEV will generate approximately 4,600 more pounds of CO_2-equivalents than the comparable ICEV (Figure 32).

BEVs will still produce a human health impact disproportionately larger than ICEVs. Increased driving range for BEVs will reduce the need for ICEV alternative transportation, although this will have little impact on HTP for BEVs. An energy-mix less reliant on coal in 2025 will reduce the HTP for BEVs, but the use of approximately twice as large battery packs in 2025 compared to 2015 will more than offset this reduction. The net effect of these changes will cause overall HTP for BEVs to increase dramatically, from 20 days of life lost to death or disability (measured in DALYs) in 2015 to 30 days in 2025 (see Figure 33). This increase is due to the fact that the vast majority of HTP for BEVs originates from mining raw materials, namely heavy metals and graphite, and significant improvements in mine safety are not anticipated especially in rural and often disadvantaged mining communities. Meanwhile, HTP for ICEVs will remain stable at 6 days, meaning that the HTP differential between BEVs and ICEVs will increase from 3.3x in 2015 to 5.1x in 2025. The remaining secondary environmental impacts for BEVs and ICEVs will all improve or remain similar – with the exception of mineral depletion potential, which will increase for BEVs owing to the use of larger battery packs.

The end result will be a changed but recognizable landscape for BEVs and ICEVs in 2025. As the technologies for BEVs and ICEVs continue to evolve, the TCO, GWP, and secondary environmental impacts will all shift to some degree. While the 44% TCO differential favors Compact ICEVs over BEVs in 2015, that variance declines to only 12% in 2025. The 23% GWP variance that favors Compact BEVs over ICEVs in 2015 will increase to 27% in 2025, but the HTP generated by BEVs will increase by more than half in 2025, representing a trade-off between greenhouse gas emissions and human health impacts.

Conclusion

ADL's comprehensive assessment of TCO, GWP, and Secondary Environmental Impacts for new BEVs and ICEVs produced in 2015 concludes that BEVs produce lower GWP but have a higher TCO and HTP over the twenty-year vehicle lifetime than do comparable ICEVs. This is the case for new vehicles produced in 2015 and will remain true for new vehicles produced in 2025 (see Figure 34). It should be noted, however, that ICEVs have a lower GWP impact in the first 3 to 4 years of operation compared to equivalent BEVs for new vehicles produced in 2015 as well as in 2025.

As time progresses, BEV technology will improve such that TCO will decline and driving range will improve. These improvements will benefit the consumer and increase the GWP differential relative to ICEVs. This increase in the GWP differential will occur despite the higher fuel economy requirements for ICEVs, which will outpace the decline in emissions from power generation associated with the changing US energy mix. The GWP for ICEVs will decline, but drivers will pay for this improvement in terms of a higher TCO.

Ultimately, improvements in technology come with a cost – and whether it is paid in dollars, greenhouse gas emissions, or human health impacts, BEVs and ICEVs both represent a complex set of economic and environmental trade-offs, in which advancements in one area are unavoidably connected to impacts in another. All of these trade-offs must be considered holistically when weighing the impacts of evolving passenger vehicle technology and the potential for wider BEV adoption in the US market.

Figure 34. Summary of Compact Passenger BEV versus Compact Passenger ICEV Impact Differences, 2015 and 2025

Impact	Vehicle Type	2015	2025	2025 vs. 2015
TCO – Thousand of Dollars	ICEV	48	49	2%
	BEV	68	54	-21%
	BEV vs. ICEV	44%	10%	
GWP – Thousands of Pounds of CO_2e	ICEV	137	107	-22%
	BEV	105	78	-26%
	BEV vs. ICEV	-23%	-27%	
HTP – DALYs	ICEV	6	6	0%
	BEV	20	30	50%
	BEV vs. ICEV	3.3x	5.1x	

Source: ADL Analysis

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Disclaimer

Appendices

Appendix A. BEV Sales

There are currently over a dozen BEV models available on the U.S. market and in 2015 nearly 66,000 BEVs were sold in the U.S., led by the Tesla Model S and the Nissan LEAF (see Table A-1). However, the BEV market has evolved to encompass a limited number of automotive segments when compared to the ICEV market. Within BEV offerings, Subcompact and Compact vehicles dominate at one end of the spectrum while Full-Size Luxury vehicles dominate at the other end.

Within BEV segments, the Full-Size segment is owned by Tesla, which, as of 2015, only produces Luxury Premium vehicles. For illustration, in 2015, the base model of Tesla, the Tesla S, had an MSRP of $72,700. Tesla has recently announced plans to compete outside of the Luxury segment with the Tesla Model 3

Table A-1. US BEV Sales by Make and Model

Note: Data excludes sales of BMW i3 vehicles that have the Range Extender option

Make	Model	2012	2013	2014	2015
Tesla	S	2,650	17,650	16,689	25,202
Nissan	Leaf	9,819	22,610	30,200	17,269
BMW	i3			2,611	3,937
Fiat	500e		2,310	5,132	6,194
VW	e-Golf			357	4,232
Chevrolet	Spark		539	1,145	2,629
Mercedes	B-Class ED			774	1,906
Ford	Focus Electric	680	1,738	1,964	1,582
smart	ED		923	2,594	1,387
Kia	Soul EV			359	1,015
Tesla	Model X				214
Mitsubishi	I-MIEV	588	1,029	196	115
Toyota	RAV4 EV	192	1,096	1,184	
Honda	Fit EV	93	569	407	
Total		**14,022**	**48,464**	**63,612**	**65,682**
YoY Growth (%)			**246%**	**31%**	**3%**

Source: InsideEVs.com

Table A-2. Top 10 States for BEV Sales in 2014

State	Sales Units	% of Total
California	28,749	47.6%
Georgia	9,945	16.5%
Washington	3,354	5.6%
Texas	2,192	3.6%
Florida	2,021	3.4%
Oregon	1,293	2.1%
Illinois	1,033	1.7%
New York	1,021	1.7%
Hawaii	865	1.4%
New Jersey	844	1.4%

Source: ZEV Facts

but that vehicle has not yet come to market. Outside of Luxury vehicles, the Compact Passenger segment is the single largest BEV segment at 45% of the total BEV market.

Geographically, California, Texas, Florida, and New York were the top four states in the U.S. for all vehicle sales between 2009 and 2014.[11] Together, these states comprised 33% of the total U.S. population and accounted for 34% of total U.S. vehicle sales in 2015. However, while California comprised 12% of total U.S. population and 11% of total vehicle sales in 2014, it accounted for a disproportionate 48% of BEV sales (see Table A-2). The geographical pattern of BEV sales has important implications for our environmental assessment of BEVs because the In-Use emissions generated by a BEV are largely driven by the energy mix of the regional power grid used to charge the vehicle's battery pack.

Appendix B. Total Cost of Ownership

B-1. Methodology

For our economic assessment, ADL decided to approach BEVs from the perspective of an individual consumer. We conducted a detailed analysis of the total cost to own a BEV versus an ICEV and we found that it is significantly more expensive to own and

Table B-1. Assumed Vehicle Miles Traveled (VMT) by Age

Vehicle Age	Survivability	VMT-Unweighted	VMT Weighted by Survivability
1	0.9900	14,231	14,089
2	0.9831	13,961	13,725
3	0.9730	13,669	13,300
4	0.9593	13,357	12,813
5	0.9412	13,028	12,262
6	0.9187	12,683	11,652
7	0.8918	12,325	10,991
8	0.8604	11,956	10,287
9	0.8252	11,578	9,554
10	0.7866	11,193	8,804
11	0.7170	10,804	7,746
12	0.6125	10,413	6,378
13	0.5094	10,022	5,105
14	0.4142	9,633	3,990
15	0.3308	9,249	3,060
16	0.2604	8,871	2,310
17	0.2028	8,502	1,724
18	0.1566	8,144	1,275
19	0.1200	7,799	936
20	0.0916	7,469	684
Total		**218,887**	**150,685**

Source: National Highway Traffic Safety Administration (NHTSA)

operate a BEV than a comparable ICEV. This is true for new vehicles sold in 2015 and, accounting for technological trends, will remain the case for new vehicles sold in 2025.

The measure we used to determine the economic impact of vehicle ownership is Total Cost of Ownership (TCO). TCO is comprised of two major cost categories: those incurred by the original equipment manufacturer (OEM) and those incurred once ownership of the

[11] Geographical sales data comes from the National Automobile Dealers Association Reports.

vehicle has passed to the consumer. TCO is a representation in dollars of how much owning a vehicle will cost over the lifetime of the vehicle and it encapsulates all of the cost inputs from a twenty-year vehicle lifecycle. We have discounted TCO figures back to 2015 based on the discount rate of 2.52% which was the average yield on 20-year US Treasuries during our analysis.

For costs incurred before the transfer of ownership, we use a measure called True Vehicle Cost (TVC). TVC encapsulates all of the cost inputs that go into making a vehicle, from designing, engineering, and manufacturing, through warranty cost and overhead. Once ownership has transferred to the consumer, costs include the In-Use costs of operating and maintaining the vehicle as well as the End-of-Life costs associated with disposing of the vehicle.

B-2. Annual Miles Driven

According to survey data, BEVs are driven an average of 27% fewer miles per year than comparable ICEVs.[12] ADL has assumed that BEV drivers are still traveling the same total distance as ICEV owners, but are using alternative modes of transportation when they travel beyond the range of their BEVs. For example, a two-car household may own both an ICEV and a BEV, using the BEV for daily commuting and the ICEV for longer trips. BEV owners may also be using other options such as rental cars, buses, trains, or planes when they travel or take longer trips.

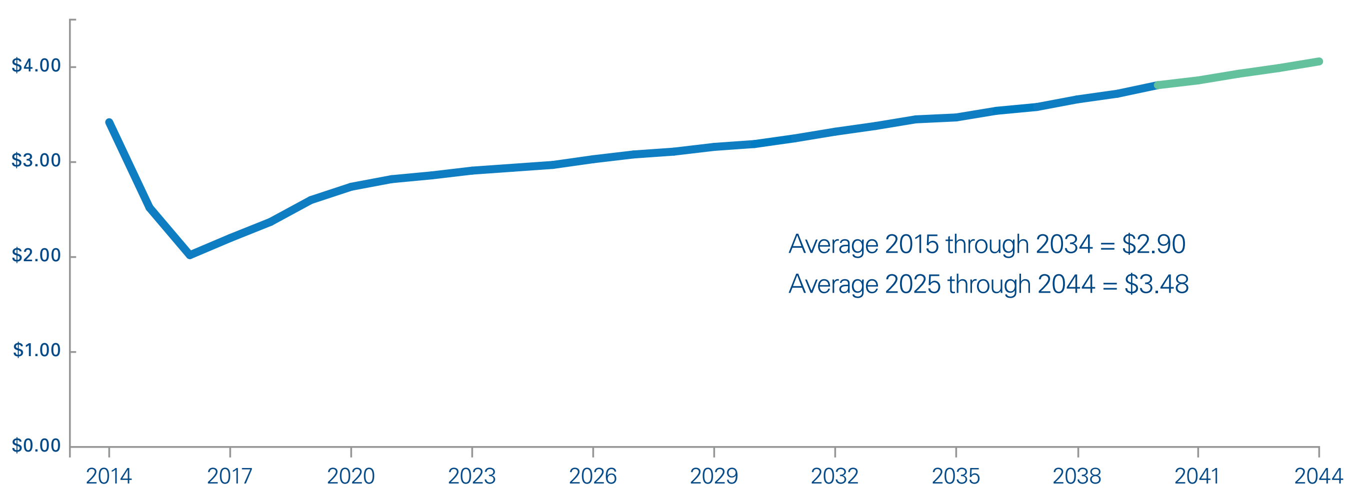
To account for the difference in miles driven, we used data from the National Highway Traffic Safety Administration (NHTSA) to estimate the number of long trips that the average owner of a BEV would make per year and we assigned all of the "alternative" mileage to a rental car (in our modeling, a comparable ICEV). Many other studies do not make assumptions about consumer behavior and compare BEVs and ICEVs as if the vehicles were being driven the same mileage. We do not believe this provides a realistic comparison from a consumer and market point of view, given today's limited driving range for BEVs and the current paucity of public charging stations. It should be noted that over the next decade as the range of BEVs increases and charging station infrastructure improves, the need for alternative transportation will decrease. Accordingly, in our 2025 modeling, alternative transportation miles account for approximately 11% of total miles.

It is important to note that we also take "survivability" into account in our mileage figures (see Table B-1). In short, we adjust a vehicle's annual miles driven by the probability that the vehicle is still in use. Hence, while NHTSA data indicates that a vehicle will be driven approximately 7,500 miles in Year 20 of its lifetime, the

[12] Based on data from The Idaho National Laboratory (INL) contained in their December 2014 report, "Plug-in Electric Vehicle Road Tax Analysis."

Table B-2. Gasoline Price Forecast 2015 through 2040 (with 2041 to 2044 Extrapolation)

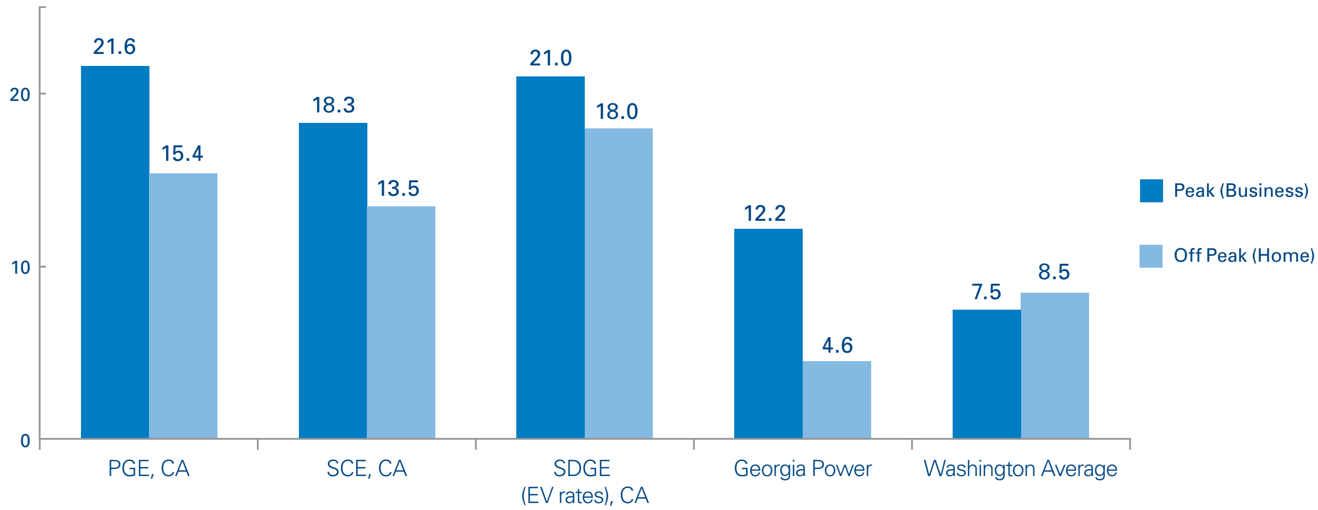
In 2015 Dollars



Source: ADL Analysis and EIA

Table B-3. Electricity Price Base Data by Selected Region in 2015

In Cents per kWh



Source: ADL Analysis

data also indicates that only 9% of vehicles are still in operation after twenty years. Put another way, 91% of vehicles will have been permanently retired before reaching Year 20, and we have weighted our mileage figures to reflect this probability. To do otherwise would assume a fleet in which all vehicles continue to be driven for twenty years after entering the market, which is unrealistic given what we know about the true In-Use lifetime of vehicles in the U.S.

B-3. Gasoline Cost

The gasoline price forecast that ADL used in modeling TCO for Compact Passenger and Mid-Size Passenger ICEVs is taken from the Energy Information Administration (EIA) (see Table B-2). It is important to note that our TCO modeling excluded federal and state taxes from EIA's gasoline price forecast. The excluded amounts were $0.18 for federal tax and $0.30 for the average of state taxes. This provides a like-to-like comparison with BEVs, as BEVs are not currently subject to an equivalent usage tax.

B-4. Electricity for TCO

In order to calculate the cost of electricity for BEVs, ADL determined both the on-peak (business) and off-peak (home) prices of electricity in the top five regions for BEV sales—Northern California, the Greater Los Angeles Area, the Greater San Diego Area, Georgia, and Washington (see Table B-3).

We used an 80% off-peak (home) charging and 20% on-peak (business) mix in order to calculate electricity costs. For 2015, we calculated the off-peak BEV sales weighted cost of electricity to be 12.5 cents per kWh and the peak to be 17.4 cents per kWh. We then forecast the Levelized Cost of Electricity (LCOE) from 2015 to 2045 based on our projected Energy Mix and LCOE data of individual sources. The LCOE in 2015 U.S. dollars is forecast to decline from $90.95/MWh in 2015 to $88.08/MWh in 2045.

Another important electricity-related cost for BEVs is the installation of the home-charging station. Based on our research, we determined that the average cost of a home-charging station is $1,225. We included this cost in our TCO for BEVs.

B-5. BEV End-of-Life

Though it can no longer be driven, ADL suspected there might still be residual value left in a BEV when it reaches the end of its lifecycle beyond the residual value of a comparable ICEV. By far the most valuable component of any BEV is the lithium-ion battery, so we looked at End-of-Life uses for 23 kWh and 34 kWh battery packs that could provide residual value for the owner.

First, we investigated the use of a lithium-ion battery pack as a stationary Energy Storage System (ESS) for home power generation sources, such as solar panels. We determined that approximately two-thirds of the initial capacity of the battery

Table B-4. Total Cost of Ownership for a 2015 Compact Vehicle ICEV versus BEV

Present Value in Dollars

Cost Category	ICEV	BEV	Difference	ICEV % Total	BEV % Total
True Vehicle Cost	17,146	29,164	70%	36%	43%
Fuel – Gasoline/Electricity	9,402	4,441	-53%	20%	6%
Insurance	11,884	13,010	9%	25%	19%
Financing	795	1,496	88%	2%	2%
State Fees	2,953	4,286	45%	6%	6%
Maintenance and Repairs	5,496	2,190	-60%	12%	3%
Home Charging Installation		1,225			2%
Battery Replacement		2,195			3%
Alternative Transportation		10,486			15%
Total	**47,676**	**68,492**	**44%**	**100%**	**100%**

Source: ADL Analysis

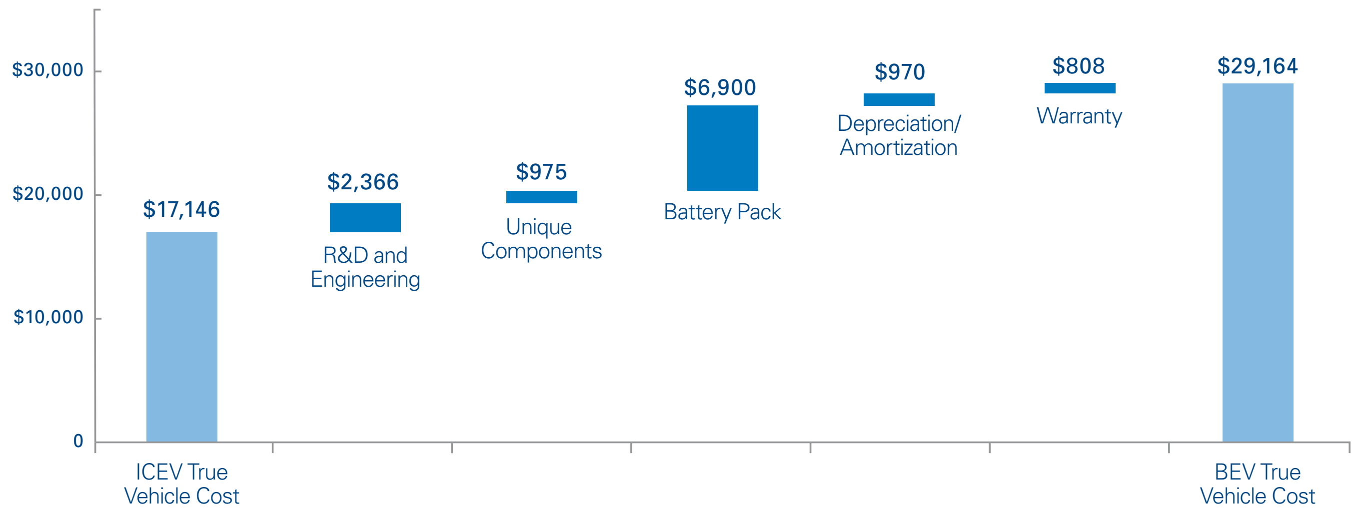
Table B-5. Total Cost of Ownership for a 2015 Mid-Size Vehicle ICEV versus BEV

Present Value in Dollars

Cost Category	ICEV	BEV	Difference	ICEV % Total	BEV % Total
True Vehicle Cost	19,114	37,865	98%	36%	44%
Fuel – Gasoline/Electricity	10,447	4,858	-53%	19%	6%
Insurance	14,485	17,171	19%	27%	20%
Financing	769	1,862	142%	1%	2%
State Fees	3,184	5,308	67%	6%	6%
Maintenance and Repairs	5,651	2,251	-60%	11%	3%
Home Charging Installation		1,225			1%
Battery Replacement		3,244			4%
Alternative Transportation		12,070			14%
Total	**53,649**	**85,854**	**60%**	**100%**	**100%**

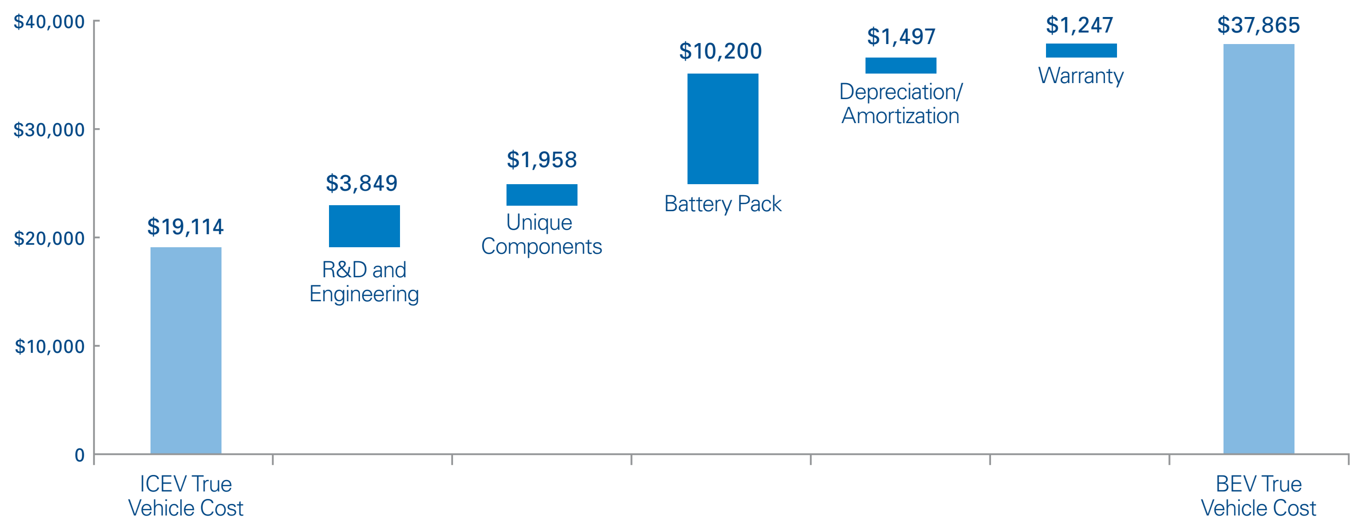
Source: ADL Analysis

Table B-6. TVC Cost Comparison for a 2015 Compact Vehicle



Source: ADL Analysis

Table B-7. TVC Cost Comparison for a 2015 Mid-Size Vehicle



Source: ADL Analysis

would remain, commencing as early as Year 7 – once a BEV battery pack has degraded that far, it may no longer provide sufficient driving range for the user. For example, if a 2015 Compact Passenger Vehicle has an initial range of only 76 miles, once the battery pack has reached two-thirds of its initial capacity it can only drive 50 miles on a single charge.

Northern California was used to determine the value from charging a lithium-ion ESS during off-peak hours and selling electricity back to the grid during peak hours. The average differential in 2015 was $0.0485, so theoretically the owner of the ESS could make a profit of between $185 and $280 annually. This corresponds to a 10-year present value of $1,750. However, the battery removal, installation, maintenance, and end-of-life disposal costs for the ESS were estimated to be between $1,500 and $2,000, thus negating any value from storing and re-selling electricity. In the future, it is possible that combining multiple battery packs—or using a single larger battery pack—could change these economics.

Next, we calculated the value of the metals used in the lithium-ion battery. We used the average composition of a lithium-ion battery pack to calculate the mass of metals present for two common types of BEV battery packs—Lithium Iron Phosphate (LFP) packs and Lithium Nickel Manganese Cobalt Oxide (NCM) packs. We examined the composition at the module level and the component level in order to identify sources of value. The cathode (approximately 32% of the weight of the pack) is comprised of the most valuable and most easily recyclable metals. In NCM battery packs, there is a significant amount of relatively valuable transition metals. In LFP packs, the only transition metal is extremely inexpensive (iron). We used September 2015 spot prices to determine the value of each metal in the battery. The NCM cathode was approximately 35 times more valuable than the LFP cathode, and the value of the NCM packs ranged from $650 to $850. Although the actual cost to recycle and smelt battery packs is not well-established, we estimated the cost would be between $500 and $1,000. Consequently, the residual value of the lithium-ion battery pack was determined to be negligible.

B-6. Results

The following tables show the results of our comprehensive TCO assessment for new vehicles produced in 2015. Tables B-7 and B-8 show the TCO results for our ICEV and BEV models by all major cost categories. Tables B-9 and B-10 show our TVC results by all major cost categories.

Appendix C. Global Warming Potential

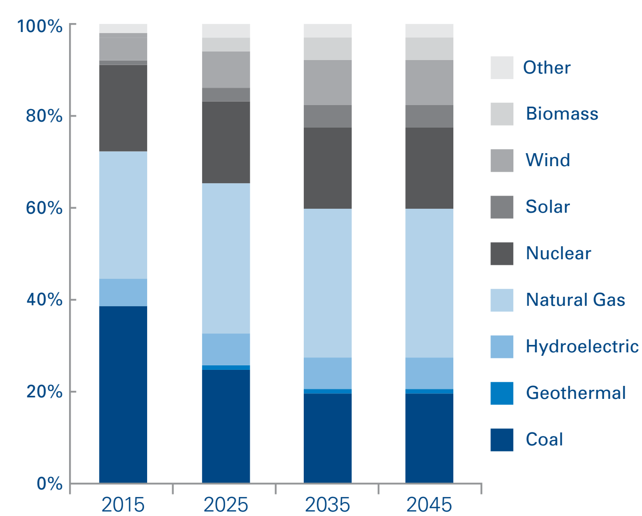
C-1. Methodology

To conduct our Global Warming Potential Assessment, we calculated the total emissions of CO_2-equivalents that would be generated by each type of vehicle over its lifecycle. This included emissions from the In-Use portion of the vehicle's lifecycle, as well as from R&D, Engineering, Vehicle Production, and End of Life.

To determine the In-Use emissions for an ICEV, we first calculated the total gallons of gasoline consumed over the lifetime of a vehicle based on a total of 150,685 miles and an assumed miles per gallon figure. We then multiplied the total gallons of gasoline consumed by an assumed emissions rate of 11,043 grams of CO_2e per gallon to arrive at total lifetime emissions. The 11,043 grams emission rate was taken from the GREET model developed by Argonne National Laboratory; this figure covers the total Well-to-Wheels emissions.

To determine the In-Use emissions for a BEV, we first calculated the total electricity required to power the vehicle based on its assumed efficiency in kWh per mile multiplied by the vehicle's lifetime total of miles travelled. Then, based on the geographical sales pattern of BEVs, we determined how much electricity would be required from each of the North

Table C-1. Forecast US Energy Mix for Generation 2015–2045



Source: ADL Analysis

American Electric Reliability Corporation (NERC) Regional Entities to service the In-Use BEV fleet. For each NERC region we determined the mix of fuels used to generate electricity and, using estimates from the Argonne GREET model of the GWP emissions for each type of fuel, we determined the weighted average emissions for each NERC (see Table C-2). Finally, we multiplied the emissions rate for each NERC by the BEV consumption of energy within that NERC, and accordingly determined the national average of emissions for an individual BEV in the current U.S. vehicle fleet.

As of 2015, BEV sales are weighted toward less carbon-intensive NERCs and the average emissions from a BEV today is lower than it would be if BEV sales were to follow the same geographical pattern as ICEV sales. It is important to note that we included the need for alternative transportation in our GWP Assessment for BEVs. We calculated that a 2015 ICEV would be driven approximately 40,000 miles more than a BEV over the 20-year lifecycle. For each BEV that we assessed, we assigned the differential in miles driven to a comparable ICEV rental car and included the associated emissions in our total GWP emissions for the BEV.

We calculated GWP for BEV and ICEV manufacturing based on the major components of each vehicle—the Body, Engine/Motor, Other Powertrain, and Battery. Key parameters for these calculations included battery pack size (kWh), vehicle horsepower, and battery and car weight (lbs). Finally, we estimated the End-of-Life emissions associated with each type of vehicle.

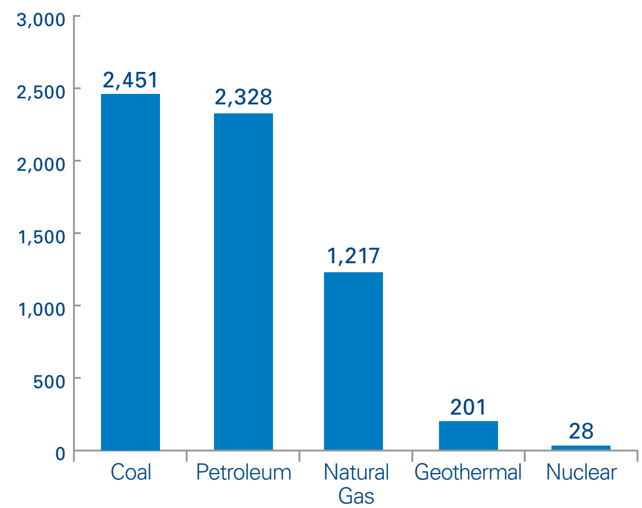
C-2. Electricity Assumptions for GWP Calculations

To calculate the In-Use GWP for BEVs, we constructed a U.S. Energy Mix forecast from 2015 to 2045 based on the EPA's recently-issued Clean Power Plan regulations covering carbon emissions (see Table C-1). We used the Argonne GREET model to determine pounds of CO_2e—which includes emissions of Carbon Dioxide, Methane, and Nitrous Oxide—that are emitted during electricity generation (see Table C-2). In terms of electricity generation, Coal, Petroleum, and Biomass are the heaviest emitters of total greenhouse gases per kWh.

In 2015, the U.S. Energy Mix is dominated by Coal, which accounts for 33.2% of total electricity generation, followed by Natural Gas at 32.7%, Nuclear at 19.5%, and Hydroelectric at 6.1% (see Table C-1 for the full breakdown). Based on regulations in the Clean Power Plan, we forecast the US Energy Mix will rely significantly less on coal over time, with natural gas and renewables making up the difference. By 2035, we forecast Coal will account for only 20% of electricity generation, while Natural Gas, Nuclear, and Hydroelectric will hold relatively steady at 33%, 18%, and 7% respectively. Wind power will have risen to 10% of total electricity generation in 2035, up from 5% in 2015.

Table C-2. Greenhouse Gas Emissions from Electricity Generation Sources

In Pounds of CO_2e per MWh



Source: ADL Analysis

We determined that the current BEV fleet will have minimal (if any) impact on Total U.S. Power Generation requirements, since the U.S. produces a very large amount of electricity annually (4.1 billion MWh in 2015). However, local transmission and distribution of electricity could pose a challenge to electricity service providers – for example, researchers have found that charging multiple BEVs at the same time in the same location can overload local distribution networks.[13]

[13] Carvalho, R.; Bunza, L.; Gibbens, R.; Kelly, F. Critical behavior in charging of electric vehicles. New J. Phys. 2015. 17.

Table C-3. GWP Emissions for a New 2015 Compact Passenger Vehicle

In Pounds of CO_2e

Category	ICEV	BEV	Diff
In-Use – Regular Miles	122,174	37,178	70%
In-Use – Alt. Transport Miles		32,195	
Battery Manufacturing		10,326	
Other Manufacturing	13,396	15,553	-16%
Battery Replacement		8,884	
End of Life	951	918	3%
Total	**136,521**	**105,054**	**23%**

Source: ADL Analysis

Table C-4. GWP Emissions for a New 2015 Mid-Size Passenger Vehicle

In Pounds of CO_2e

Category	ICEV	BEV	Diff
In-Use – Regular Miles	135,749	40,663	70%
In-Use – Alt. Transport Miles		35,764	
Battery Manufacturing		15,264	
Other Manufacturing	14,855	16,810	-13%
Battery Replacement		13,133	
End of Life	1,054	1,138	-8%
Total	**151,658**	**122,772**	**19%**

Source: ADL Analysis

C-3. Results

Tables C-3 and C-4 show the results of our GWP assessment for 2015. These tables report the total GWP emissions for the BEVs and ICEVs we modeled, broken out by the major sources of GWP emissions.

Appendix D. Secondary Environmental Impacts

D-1. Methodology

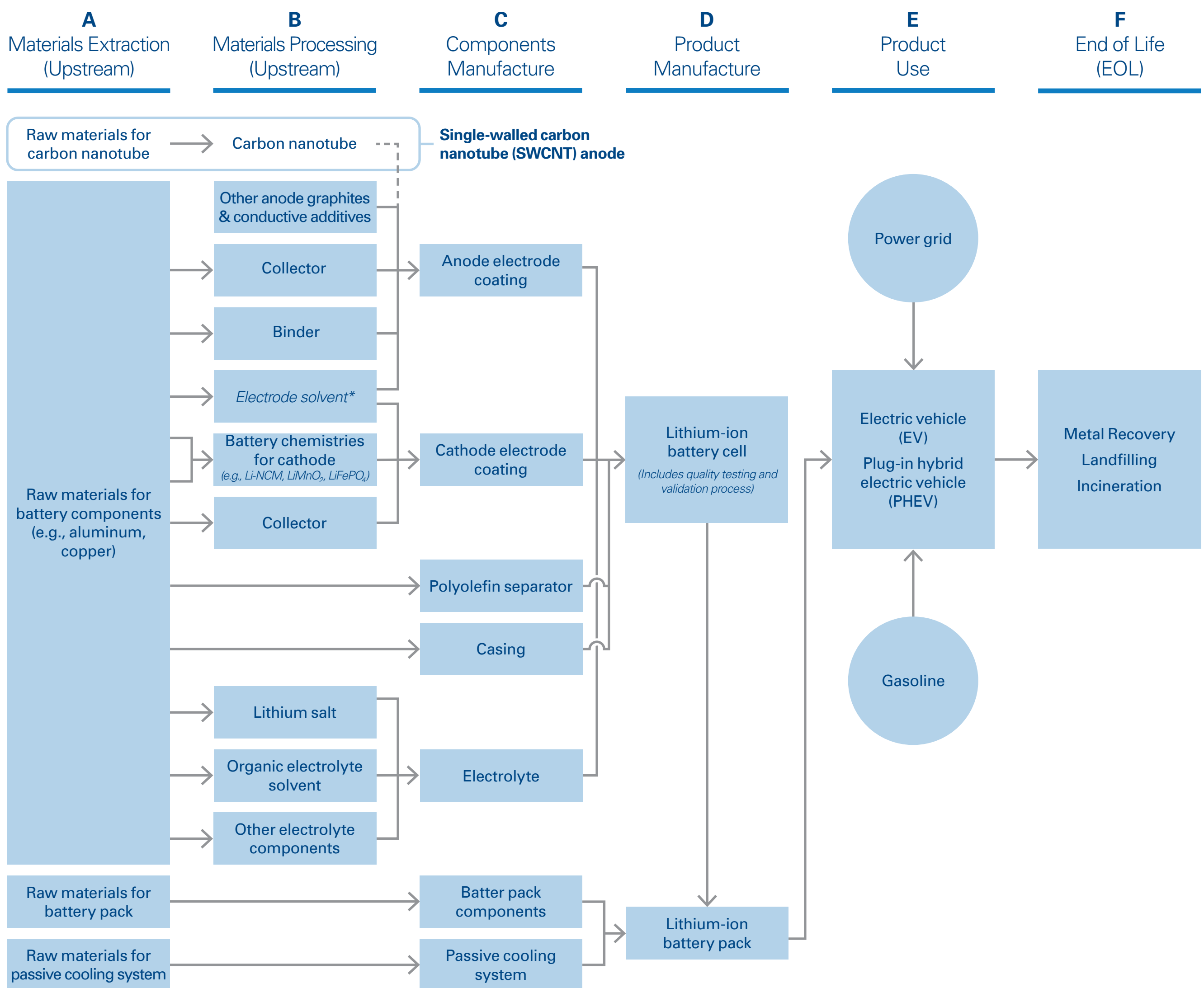
For our assessment of Secondary Environmental Impacts, we leveraged the methodology defined by Troy Hawkins et al. in "Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles," which examines all supply chains relevant to the environmental impact generated by BEVs and ICEVs during vehicle production, In-Use, and end of life.[14] By way of illustration, Table D-1 outlines a generic process flow for the full lifecycle of a lithium-ion battery.

We examined three measures of toxicity and two measures of natural resource depletion. The toxicity measures we examined were human toxicity potential (HTP), freshwater toxicity potential (FTP), and terrestrial toxicity potential (TTP). The natural resource depletion measures we examined were mineral depletion potential (MDP) and fossil fuel depletion potential (FFDP). Definitions for these Secondary Environmental Impacts are as follows:

- Human Toxicity Potential (HTP) is a calculated index that reflects the potential harm to humans from a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and also its potential dose.
- Freshwater Toxicity Potential (FTP) is a calculated index that reflects the potential harm to freshwater organisms from a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and also its potential dose.
- Terrestrial Toxicity Potential (TTP) is a calculated index that reflects the potential harm to terrestrial organisms from a unit of chemical released into the environment and is based on both the inherent toxicity of a compound and also its potential dose.
- Mineral Depletion Potential (MDP) is a measure of consumption of natural resources, specifically those that are mined, expressed in grams of iron-equivalents.

[14] Hawkins, T.R.; Majeau-Bettez, G.; Singh, B.; Strømman, A.H. Comparative environmental life cycle assessment of conventional and electric vehicles. J. Ind. Ecol. 2012. 17 (1), 53-64.

Table D-1. Generic Process Flow Diagram for Li-ion Battery for Vehicles



Source: EPA

The majority of Human Toxicity Potential (HTP) from BEVs arises during the Materials Extraction process due to miners being exposed to heavy metals in an often uncontrolled environment. As battery manufacturing progresses, human exposure declines due to increased controls and safety procedures in manufacturing plants.

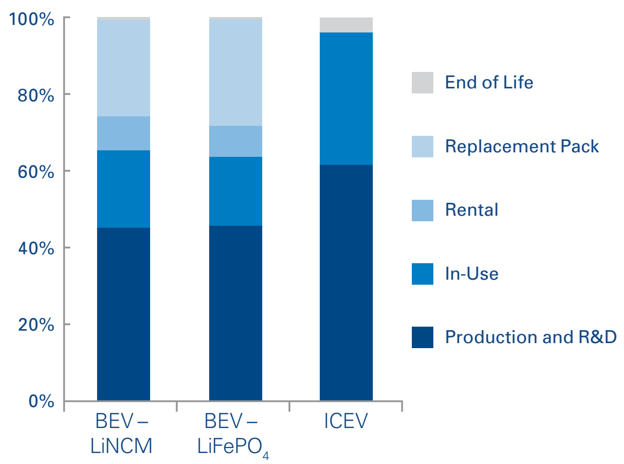
- Fossil Fuel Depletion Potential (FFDP) is a measure of consumption of fossil fuels, expressed in grams of oil-equivalents.

Our toxicity measures are presented in equivalent units of para-dichlorobenzene (p-DCB), a standard for measuring toxicity across substances, species, and ecosystems. For HTP, we then converted units of p-DCB into disability-adjusted life years (DALYs) using the USEtox 2.0 model developed under the United Nations Environment Program (UNEP). In order to ensure the accuracy of our human toxicity measures, we compared our results to those presented by other studies of the human health impact of BEVs and ICEVs.

D-2. Results

The following tables display the results of our Secondary Environmental Impacts assessment for 2015. Tables D-2 and D-3 refer to our HTP assessment, Tables D-4 and D-5 refer to the other toxicity potentials we assessed, and Tables D-6 and D-7 display our natural resource depletion potentials.

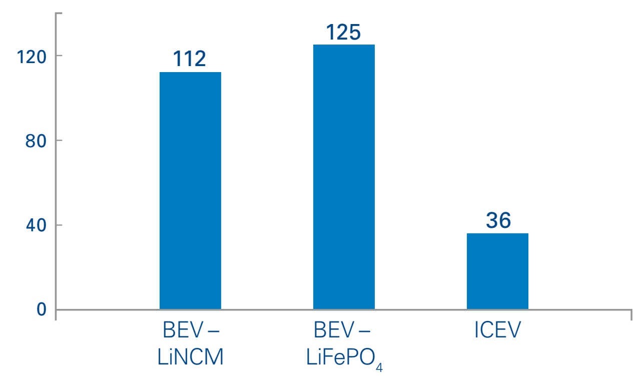
Table D-2. HTP by Lifecycle Component for a 2015 Compact Vehicle



Source: ADL Analysis

Table D-3. Human Toxicity Potential for 2015

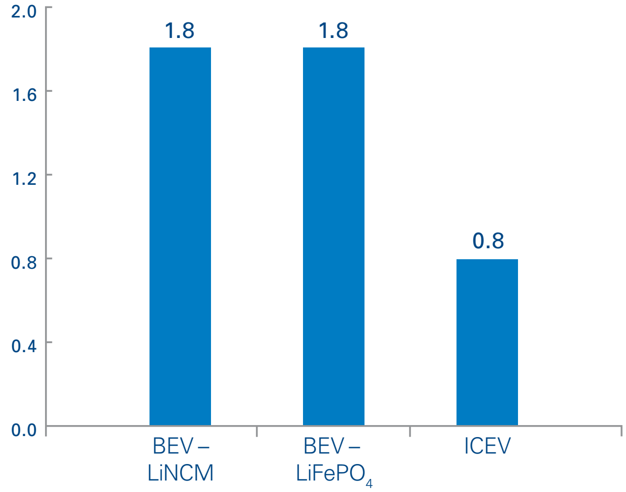
In Grams of 1,4-Dichlorobenzene-equivalents per Mile



Source: ADL Analysis

Table D-4. Freshwater Toxicity Potential for 2015

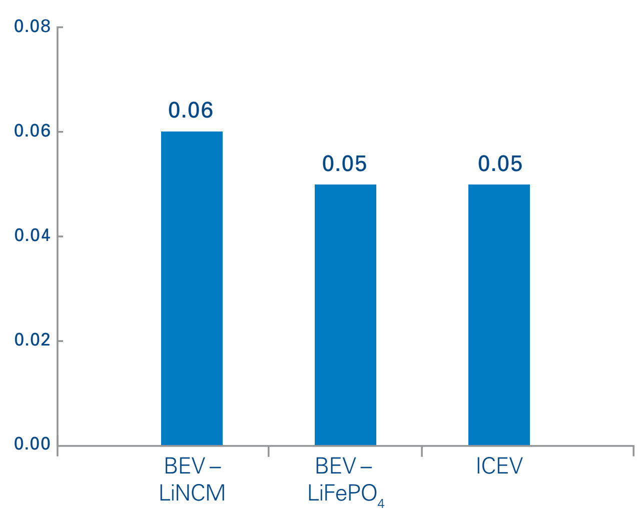
In Grams of 1,4-Dichlorobenzene-equivalents per Mile



Source: ADL Analysis

Table D-5. Terrestrial Toxicity Potential for 2015

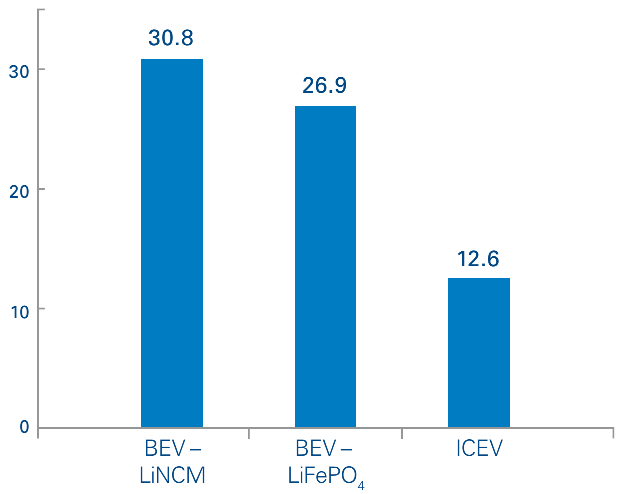
In Grams of 1,4-Dichlorobenzene-equivalents per Mile



Source: ADL Analysis

Table D-6. Mineral Depletion Potential for 2015

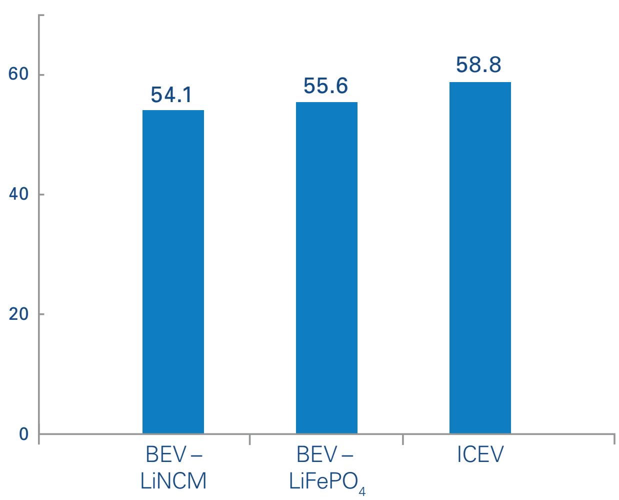
In Grams of Fe-equivalents per Mile



Source: ADL Analysis

Table D-7. Fossil Fuel Depletion Potential for 2015

In Grams of Oil-equivalents per Mile



Source: ADL Analysis

Appendix E. 2025 Forecast

E-1. Technology Trends

ADL has developed a technology forecast for BEVs and ICEVs out to 2025 and projected our 2015 results for TCO, GWP, and Secondary Environmental Impacts for new vehicles produced in 2025. By far, the most significant developments concern battery pack technology. For historical context, in 2010, when the Nissan LEAF debuted, lithium-ion battery packs cost $1,126/kWh. The price dropped by nearly 50% the next year, to $620/kWh, and the cost of lithium-ion battery packs for BEVs has declined significantly (approximately 70%) over the next 5 years to reach $300/kWh in 2015. It should go without saying that any decrease in battery cost improves the picture for BEVs. ADL believes that the cost will continue to decline, albeit at a much slower pace due to the maturation of battery pack technology. We forecast that the battery cost will reach $120/kWh in 2025 and $100/kWh in 2035 (see Table E-1).

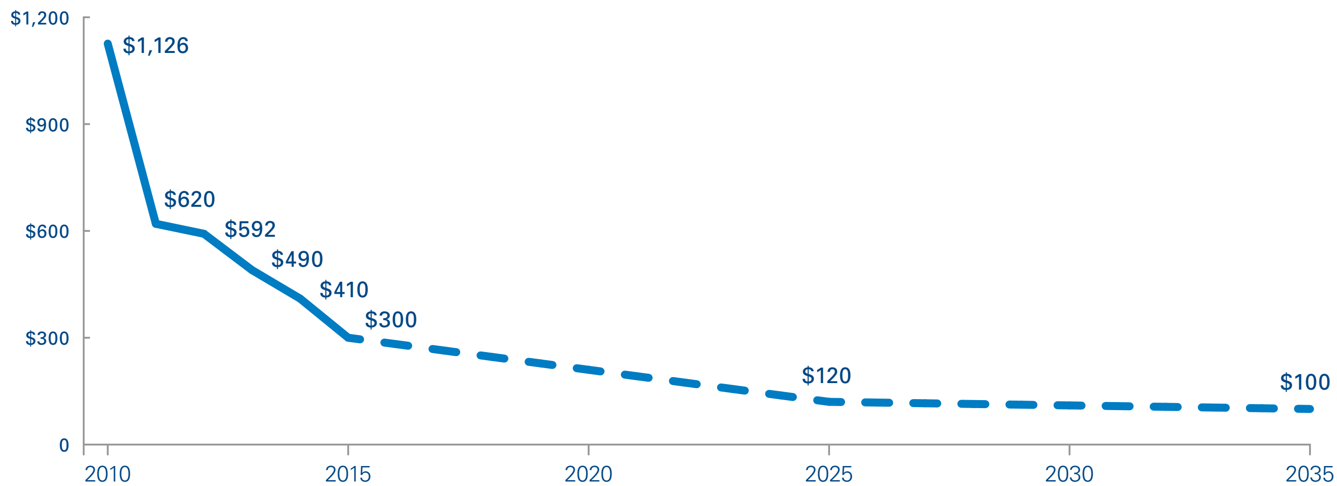
The BEV driving range, the cost of batteries, and the influence of regulation and policy are expected to be key drivers in the evolution and market penetration of BEVs through 2025. Supplementing our analysis with interviews with select OEMs, battery manufacturers, and suppliers, ADL forecasts that the energy density for BEV batteries will increase 50-60% in ten years, and as battery packs become cheaper, we forecast that larger packs will be used in BEVs to further enhance vehicle range and performance. This will double the driving range of mass market BEVs from their current state of 80-100 miles.

Regulatory and policy tools remain uncertain, but the California Air Resource Board is likely to be a key driver of BEV impact. The ARB Chair, Mary Nichols, is pushing for regulations today that could dramatically change the landscape for BEVs and ICEVs. However, without attendant performance and cost improvements, we believe it is unlikely that consumer acceptance of BEVs will increase dramatically in the next 10 years. The regulatory environment for ICEVs is clearer and we forecast that, between 2015 and 2025, OEMs will adopt a variety of new technologies to meet stricter CAFE standards. The technological trends for improving ICEV fuel economy will impact the TCO for ICEVs, albeit not as dramatically as battery technology innovations will impact the TCO for BEVs.

We estimate that technological trends related to ICEVs will reduce fuel consumption per vehicle by 29.2% in 2025 compared to 2015, while increasing the TVC by $980 to $1,1160 per vehicle

Table E-1. Historical and Forecast Lithium-Ion Battery Pack Cost

In Dollars per kWh



Source: ADL Analysis

(we leveraged the cost estimates in "Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles" – it should be noted that some OEMs may forecast higher costs).[15] The addition of turbocharging and other enhancements to the ICEV engine will cause the largest shift, accounting for an 11.9% reduction in fuel consumption while increasing the TVC per vehicle by $600 to $800. Improvements to the body and structure of the vehicle, primarily involving the adoption of light-weight materials, should lead to an additional 4.8% reduction in fuel consumption, while increasing the cost per vehicle by $100 to $200. Other important innovations include improved transmission, the adoption of electric steering, and improvements to the climate control and engine cooling systems. Each of these changes will only have a slight impact on fuel economy and cost per vehicle, but taken together they have a notable impact on the TCO for ICEVs.

[15] Committee on the Assessment of Technologies for Improving Fuel Economy of Light-Duty Vehicles, Phase 2; Board on Energy and Environmental Systems; Division on Engineering and Physical Sciences; National Research Council. Cost, Effectiveness and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. The National Academies Press: Washington DC, 2015.

E-2. 2025 Results

The following tables show TCO, GWP, and Secondary Environmental Impacts for new vehicles produced in 2025, in accordance with our technology trends forecast. Tables E-2 and E-3 show TCO, Tables E-4 and E-5 show GWP, and Tables E-6 through E-10 show the Secondary Environmental Potentials for new vehicles produced in 2025.

It is important to note that our 2025 numbers for ICEVs show a reduction in In-Use GWP emissions per vehicle compared to 2015 due to increased ICEV MPG. At the same time, our 2025 numbers reflect an improvement in BEV efficiency, although this is mitigated by an increase in battery size (which in turn results in more range). Our 2025 estimates also reflect a reduction in the carbon intensity of power generation due to proportionally less coal being used and a higher percentage of renewables (see Table C-2 above for details). Our 2025 forecast assumes that BEV sales continue with the same geographical sales pattern as 2015, but if the sales pattern were to migrate to follow the ICEV national pattern, the 2025 In-Use emissions from a BEV would be approximately 8% higher than the results shown below. The need for alternative transportation will have decreased by 2025, and a new 2025 ICEV will be driven approximately 16,000 more miles than an equivalent BEV.

Table E-2. Total Cost of Ownership for a 2025 Compact Vehicle ICEV versus BEV

In Dollars at Present Value

Cost	ICEV	BEV	Difference	ICEV % Total	BEV % Total
True Vehicle Cost	18,126	24,749	37%	37%	45%
Fuel – Gasoline/Electricity	9,113	3,708	-59%	19%	7%
Insurance	11,975	12,596	5%	25%	23%
Financing	853	1,239	45%	2%	2%
State Fees	3,068	3,767	23%	6%	7%
Maintenance and Repairs	5,496	2,893	-47%	11%	5%
Home Charging Installation		1,000			2%
Battery Replacement		2,795			5%
Alternative Transportation		1,655			3%
Total	**48,631**	**54,402**	**12%**	**100%**	**100%**

Source: ADL Analysis

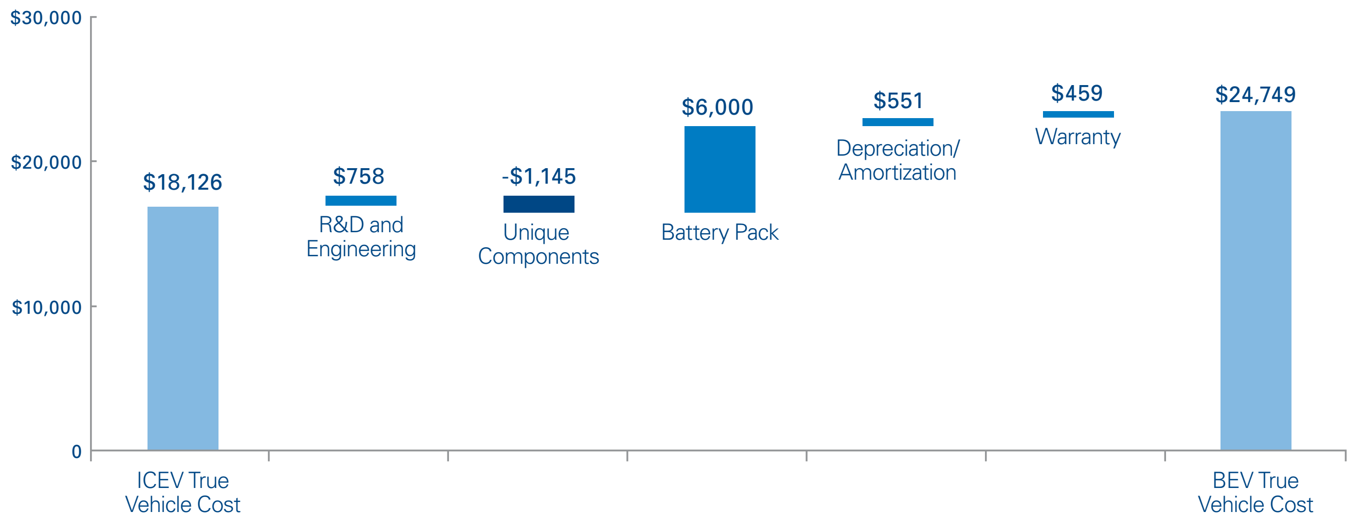
Table E-3. Total Cost of Ownership for a 2025 Mid-Size Vehicle ICEV versus BEV

In Dollars at Present Value

Cost	ICEV	BEV	Difference	ICEV % Total	BEV % Total
True Vehicle Cost	20,274	30,385	50%	37%	46%
Fuel – Gasoline/Electricity	10,125	4,038	-60%	18%	6%
Insurance	14,651	16,100	10%	27%	24%
Financing	836	1,426	70%	2%	2%
State Fees	3,320	4,429	33%	6%	7%
Maintenance and Repairs	5,651	2,974	-47%	10%	5%
Home Charging Installation		1,000			2%
Battery Replacement		3,745			6%
Alternative Transportation		1,903			3%
Total	**54,857**	**66,000**	**20%**	**100%**	**100%**

Source: ADL Analysis

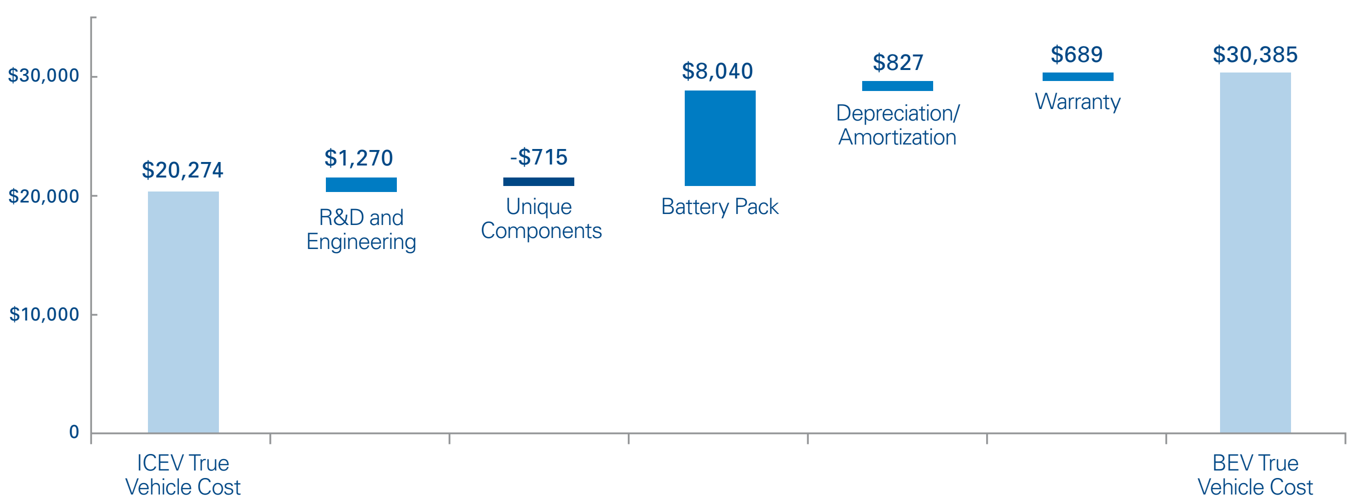
Table E-4. TVC Cost Comparison for a 2025 Compact Vehicle



Source: ADL Analysis

Table E-5. TVC Cost Comparison for a 2025 Mid-Size Vehicle

In Dollars per kWh



Source: ADL Analysis

Table E-6. GWP Emissions for a New 2025 Compact Passenger Vehicle

In Pounds of CO_2e

Category	ICEV	BEV	Difference
In-Use - Regular Miles	92,513	32,784	65%
In-Use - Alt. Transport Miles		4,419	
Battery Manufacturing		13,693	
Other Manufacturing	13,396	16,096	-20%
Battery Replacement		9,818	
End of Life	951	1,057	-11%
Total	**106,860**	**77,866**	**27%**

Source: ADL Analysis

Table E-7. GWP Emissions for a New 2025 Mid-Size Passenger Vehicle

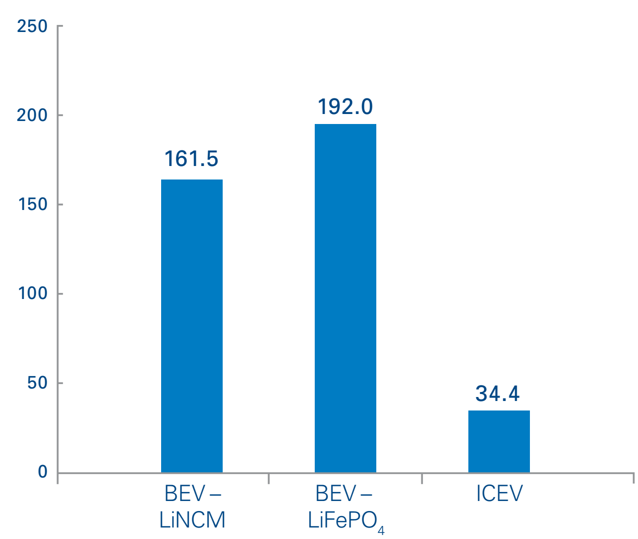
In Pounds of CO_2e

Category	ICEV	BEV	Difference
In-Use - Regular Miles	102,793	35,857	65%
In-Use - Alt. Transport Miles		4,908	
Battery Manufacturing		18,349	
Other Manufacturing	14,855	17,603	-18%
Battery Replacement		13,156	
End of Life	1,054	1,276	-21%
Total	**118,702**	**91,148**	**23%**

Source: ADL Analysis

Table E-8. Human Toxicity Potential for 2025

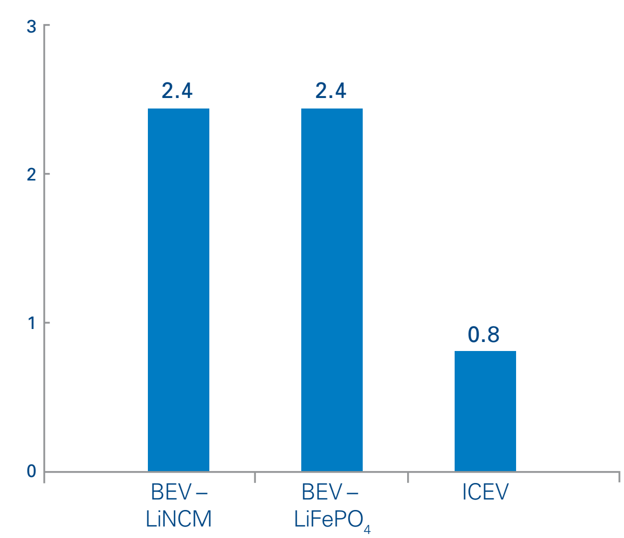
In Grams of 1,4-Dichlorobenzene-equivalents per Mile



Source: ADL Analysis

Table E-9. Freshwater Toxicity Potential for 2025

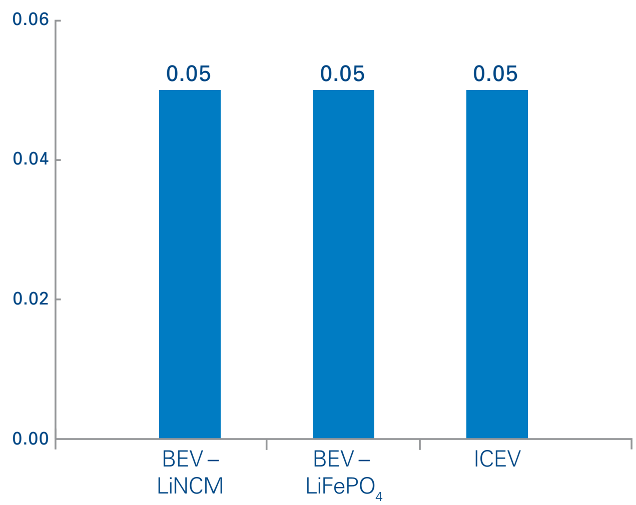
In Grams of 1,4-Dichlorobenzene-equivalents per Mile



Source: ADL Analysis

Table E-10. Terrestrial Toxicity Potential for 2025

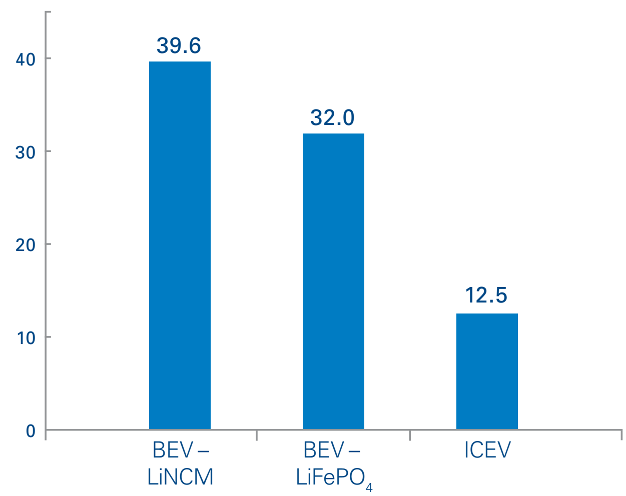
In Grams of 1,4-Dichlorobenzene-equivalents per Mile



Source: ADL Analysis

Table E-11. Mineral Depletion Potential for 2025

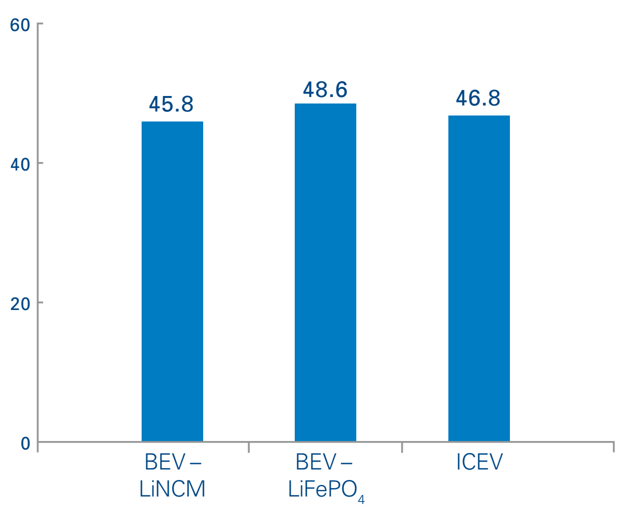
In Grams of Fe-equivalents per Mile



Source: ADL Analysis

Table E-12. Fossil Fuel Depletion Potential for 2025

In Grams of Oil-equivalents per Mile



Source: ADL Analysis

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